

Final Report on

Robotic Manipulator Project

June 1, 2001

By

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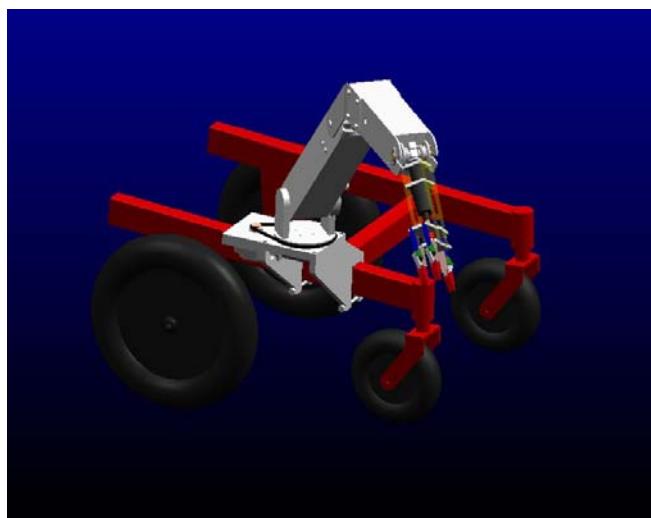
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ABSTRACT

The 2000-2001 Gateway design team engaged in a nine-month design process to develop a robotic arm that is mounted to a wheelchair with the specific goal of helping paraplegics and quadriplegics function in their immediate environment. This year's team consisted of students from The Ohio State University, Wright State University, and Sinclair Community College and was sponsored by the Gateway Engineering Coalition. The educational object of this project was to teach the participants the skills to solve an engineering design problem in a cooperative environment.

This report presents a general background of the project along with a description of the overall group dynamics. The report is organized into two main sections: the design and manufacture of the arm, which was the major task for Wright State and Sinclair, and the controls system of the arm, for which Ohio State was responsible. The design and manufacture sections describe the design of the base, lower arm, forearm, and gripper. The controls portion is broken into sections covering motor testing, controls hardware, and controls software and strategy.

Several conclusions that were drawn and could be used to improve the arm include: 1) the center of gravity of the arm should be lowered, 2) an attempt should be made to make the arm lighter, 3) electrical current should be drawn off of both wheelchair batteries instead of just one, 4) all of the motors should be of the same type, preferably DC, to simplify the control scheme, 5) a new controller, other than the OOPic, should be considered, and 6) the gripper should be examined and possibly modified so that it can grip small objects.

ACKNOWLEDGEMENTS

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Special thanks to the faculty advisors, Dr. Gary Kinzel of The Ohio State University, Dr. James Menart of Wright State University, and Beth Johnson and Scott Hawkins at Sinclair Community College. Their guidance and leadership have made this project a highlight in the college experience of the participating students.

The participants at Ohio State would like to thank Dr. Giorgio Rizzoni for his knowledge and assistance in motor testing, Ted Harper for fabrication of the motor test stand mount, Joe West for motor testing troubleshooting, and Chris Fearon and Fred Griesemer for their continued research support and guidance. Carl Kollar, of Diverse Electronic Services, was also a great help in choosing electrical hardware and offering advice. A special thanks also goes out to Gary Gardener and Keith Rogers for their project saving machining in the waning hours of the final presentation.

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PROJECT HISTORY & OVERVIEW

1.1 GATEWAY COALITION PROGRAM BACKGROUND

The Gateway Coalition is an organization comprising seven institutions dedicated toward advancing engineering education. Supported by the Engineering Directorate of the National Science Foundation, the Gateway Coalition sponsors several projects, including this multi-university senior design project. The system developed for this project is a wheelchair-mounted robotic arm to assist paraplegics and quadriplegics in their daily lives. Three institutions are currently collaborating to develop the robotic arm: Ohio State University, Wright State University, and Sinclair Community College.

The multi-university project has continued since 1995, and the robotic arm for a wheelchair has been used as a project since 1996. A brief description of the previous years' efforts is given in the following sections. This is followed by the details on the project for the 2000-2001 academic year.

1.2 1996-1997 DESIGN

The 1996-1997 final design is illustrated in Figure 1.1. This device was a 3 link, 6 degree of freedom device with a transmission system consisting of cables and transmission pulleys. The purpose of the transmission pulleys was to keep the motors at the base of the robot, thus decreasing the torque on the arm. Unfortunately, a mistake was made in the initial torque analysis, so inappropriate motors, which were not strong enough to easily move the arm, were selected. Its overall size complicated manufacturing requirements, and the predicted high maintenance costs also hindered the design.

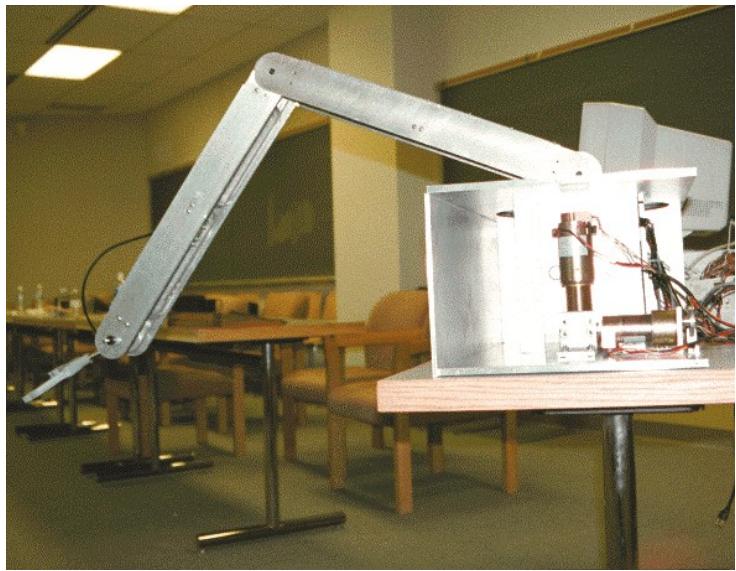


Figure 1.1 - 1996-1997 Final Design

1.3 1997-1998 DESIGN

A solid model of a design concept proposed by the 1997-1998 Ohio State team is seen in Figure 1.2. This design featured 5 degrees of freedom, with vertical motion controlled by a lead screw and horizontal motion accomplished by a motor at the elbow joint. This design differed significantly from the first design in that no cables or pulleys were used, because the motors are mounted directly on each joint (motor-on-joint control). Lower assembly and maintenance costs were the primary advantages of this design over the cable and pulley system. Another feature of this design is that it utilized more off-the-shelf parts. A drawback however, was that the required off-the-shelf components were quite expensive. It was also questionable whether the structure of the arm was rigid enough to support the torque produced by both the object to be picked up and the motors required to manipulate the arm.

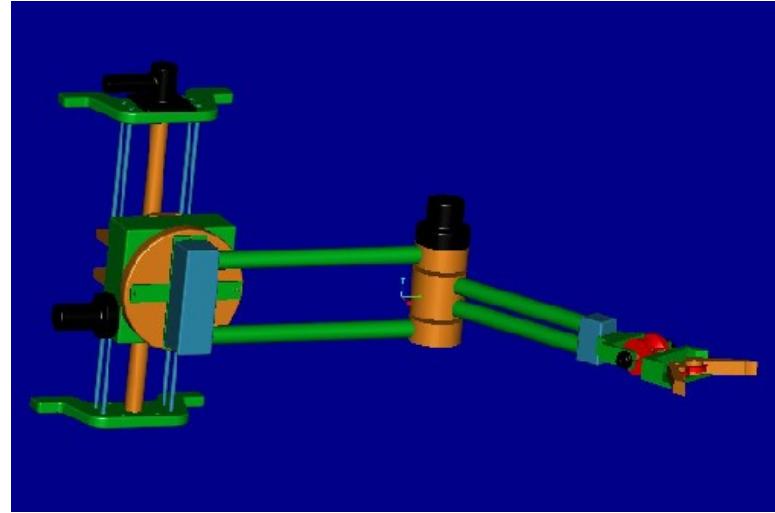
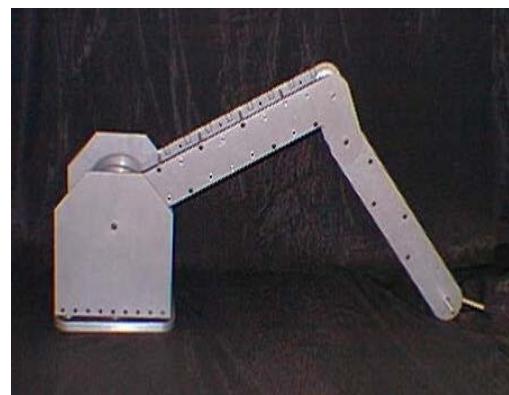


Figure 1.2 – Ohio State’s 1997-1998 Initial Design

The final 1997-1998 design (pictured in Figures 1.3 and 1.4) incorporated a transmission system similar to that of the previous year’s design. Some of the improvements included the addition of a knuckle joint and a more compact rotating base. This design was structurally and functionally better than the previous year’s design. However, it was very expensive due to the large amount of machining required, and it was never mounted to a wheelchair. Another drawback of this design was that the gripper could only be actuated in one direction. It was spring-loaded in the open position and closed by a cable, which was wound with a small motor.



*Figure 1.3 - 1997-1998 Final Design
(Folded Position)*



*Figure 1.4 - 1997-1998 Final Design
(Extended Position)*

1.4 1998-1999 DESIGN

Figure 1.5 is a solid model of the 1998-1999 initial design. This design utilized motor-on-joint control and square extruded aluminum tubing in an attempt to reduce the complexity and machining costs of the arm. Another advancement was the attempt to control the gripper motion in both directions. Additionally, this was also the first year that the robot was actually mounted to a wheelchair.

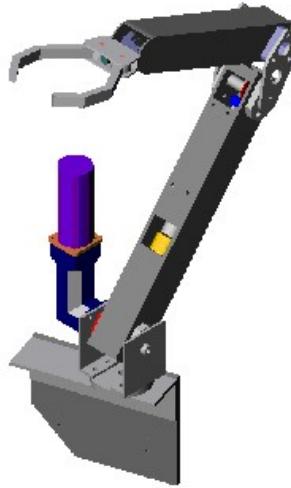


Figure 1.5 - 1998-1999 Initial Design

Figure 1.6 is a photograph of the prototype that was built. One of the main shortcomings of this design was that the gripper was very bulky and could not produce enough force to lift a payload. The shoulder motor extended about 8 inches from the side of the joint, severely inhibiting the passage of the wheelchair through standard doorways. Finally, although the arm was mounted to the wheelchair, the base rotation failed to function due to both an undersized bearing and motor at the base.

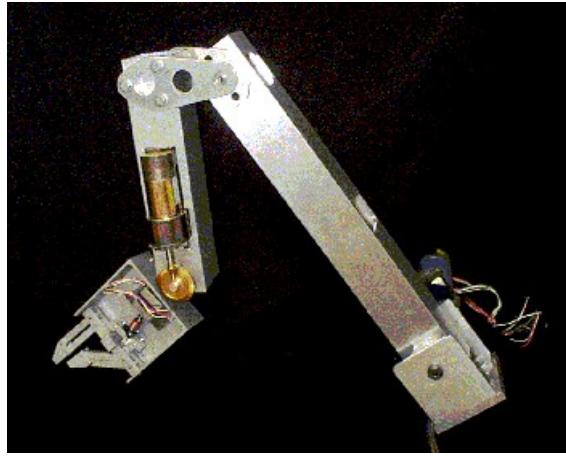


Figure 1.6 - 1998-1999 Final Design

1.5 1999-2000 DESIGN

Seen in Figure 1.7, the 1999-2000 design utilized six degrees of freedom in the arm and was mounted to a wheelchair. The large range of motion was made possible by two motors located at the shoulder, controlling the twist and bend motions, as well as a motor controlling the elbow bend. The arm also featured a three-point underactuated gripper connected to a compact differential gear set, which permitted both twist and bend at the wrist.

The final design was not without drawbacks, however. The entire arm assembly was heavy, weighing over 40 pounds, and requiring at least two people to mount the arm to the wheelchair. Extensive machining also increased the manufacturing costs. Additionally, the arm could only lift a 1-kilogram (2.2 pound) payload.



Figure 1.7 - 1999-2000 Final Design

1.6 2000 GRADUATE STUDENT DESIGN

Ohio State University graduate student Chris Fearon produced a completely enclosed design in the summer of 2000, as seen in Figure 1.8. His design incorporated 2.5-inch square tubes throughout the length of the arm, and the shoulder bend motor was located within the tubing. The motor for the shoulder twist rotation was placed beneath a compact mounting plate. The smaller design was lighter in overall weight than the 1999-2000 design. The primary drawback to the design was its cost, requiring over \$10,000 for extensive machining and fabricating. Furthermore, mounting to the wheelchair remained difficult due to the two-piece clamping brackets.



Figure 1.8 - 2000 Graduate Student Design

1.7 MARKET ANALYSIS

Rehabilitation robotics in general was studied by conducting literature and patent searches. The patent search did not reveal any existing patents for rehabilitation robotics in particular, but some specific components have been patented such as grippers. The literature search revealed many interesting facts about the state of rehabilitation robotics today. These findings are discussed in the following paragraphs.

The market for such assistive robotic products was found to be somewhat limited, as robots are an alternative only for individuals who may have a deficiency in manipulation ability. Only about 10% of the population has some sort of handicap, and much less have both lower and upper body mobility impairments. The simple fact that only those individuals with both upper and lower body handicaps will use the product limits the market. Those benefiting from a robotic arm must also not be so severely handicapped that they cannot reasonably control a joystick or other input device, further limiting the market. Therefore, it is estimated that of the approximately 1.5 million people who are confined to electric wheelchairs in the United States, between 100,000 and 500,000 could benefit from a robotic arm based on the type and extent of their disability. These numbers indicate that there is a market for a rehabilitation robot, even

though it may be limited. Furthermore, if one looks at the number of assistive robotic products sold as compared to the number of people that could benefit from such a product, it is obvious that only a very small portion of these individuals are currently benefiting from rehabilitation robots. This suggests that there is still a need for such a product if it could be designed to be affordable and efficient.

Since the product is aimed at individuals who have a deficiency in manipulation ability, the primary focus of such a device is to provide the user with a device that aids them in performing day-to-day manipulation tasks. Other groups have conducted research to determine the impact on the life of the user by such a robotic device. A study was performed by creating a profile of an individual with a severe manipulation disability. This profile was defined as a person having sedentary strength and no use of reaching, handling, and fingering. The *Dictionary of Occupational Titles*, which defines all jobs in terms of different levels of manipulation abilities, was then used to find the number of possible types of jobs that an individual with this particular profile could hold. The study found 40 job descriptions that this type of individual would be able to perform. These jobs consisted of primarily professional, technical, and managerial jobs. The study then made the assumption that with the aid of an assistive robotic product, the same individual would marginally increase their manipulation ability. The profile was redefined as a person having occasional and then frequent use of reaching, handling, and fingering skills. An individual with occasional use of these skills was then shown to be capable of performing approximately 300 jobs. The individual with frequent use of these skills was shown to be capable of performing over 1100 jobs. The results of this study alone demonstrate the impact a rehabilitation robot would have on the lives of potential beneficiaries and validates the attempt to design such a device.

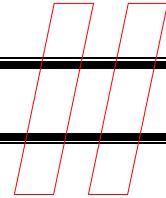
There have been a number of attempts thus far to create a rehabilitation robot that is both affordable and effective. A list of such products is shown in Table 1 below. Only three of the commercial endeavors shown in the table (Rehab Robotics, Exact Dynamics, and Rehabilitation Technologies) are actively marketing and supporting their product. The Raptor, by Rehabilitation Technologies, began sales in 2000 and has not had enough marketing time to measure its sales performance. As can be seen from the table, many of these products have not been successful, and no one product has had overwhelming

success. There are many factors which contribute to the failure of these previous attempts, including poor user interface, isolation from clinical reality, the cost benefit is not justified, lack of portability, poor organization, and lack of capital funds. All of these factors must be taken into serious consideration when attempting to design a rehabilitation robot.

Table 1.1 – Previous Attempts at Marketing Robotic Arm

Product Name	Country	Company	Type	Approx. Cost	Approx. # Sold	Where Sold
Prab Command	USA	PRAB Robotics	Vocational Workstation	\$48,000	20	Worksites, Rehab Centers
DeVar	USA	Independence Works, Inc.	Vocational Workstation	\$100,000	3	Clinical Evaluation
Manus	Nether-lands	Exact Dynamics	Wheelchair Mountable	\$35,000	50	Dutch Users
Handy 1	UK	Rehab Robotics	Mobile Base, Feeding Unit	\$6,000	140	Individual Users
Helping Hand	USA	Kinetic Rehabilitation Instruments	Wheelchair Mountable	\$9,500	10	Clinical and Research Evaluation
Papworth Arm	UK	Papworth Group	Wheelchair Mountable	\$8,000	5	Clinical and Research Evaluation
RAID	UK, France, Sweden	Oxford Intelligent Machines	Vocational Workstation	\$55,000	9	Clinical Evaluation
Arlyn Arm	USA	Arlyn Works	Education, Vocational Workstation	\$30,000	0	
Sidekick	USA	Robotic Assistance Corporation	Mobile Base		0	
Raptor	USA	Rehabilitation Technologies	Wheelchair Mountable	\$11,950	N/A	Unknown
Robotic Assistive Appliance	Canada	Neil Squire Foundation	Vocational Workstation	\$23,000	7	Clinical, Rehab, and Industry

It is also worth noting that the price and performance of a robotic aid is linked to the complexity of its design. For example, fewer degrees of freedom will lead to a device with less capability. However, this fact alone does not mean that simpler robotic aids will not be useful. The important characteristic is whether the robotic aid will meet the needs of the consumer.



COALITION DYNAMICS

2.1 PARTICIPANTS

The participants in the 2000-2001 project at each of the schools are listed below next to their respective institutional logo.

Table 2.1 – 2000-2001 Gateway Coalition Team Members

OHIO STATE UNIVERSITY



Corey Johnson
Tim Kocher
Curt O'Donnell
Michael Stevens
Aaron Weaver
Jeff Webb

WRIGHT STATE UNIVERSITY



Shawn Riley
Jason Ruge
Lawrence Thomas
Eric Yu

SINCLAIR COMMUNITY COLLEGE



Brad Cutting
Chris Shirkey
Tim Trepanier
Step II Machining & Manufacturing Class

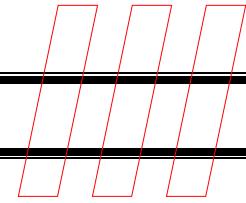
2.2 COMMUNICATION TECHNIQUES

Throughout the course of this project, three primary modes of communication provided the means for exchanging information and successfully collaborating between the teams. E-mail was an effective way for the groups to relay data and ideas. Weekly teleconferences were scheduled to maintain regular communication between groups and to address ideas and concerns in a more personal manner. The Gateway Coalition web pages were extremely helpful in transferring large data files and for keeping the other schools informed on progress.

Additionally, the groups met together at the beginning of the academic year to exchange initial design ideas, formulate project goals, and establish communication arrangements. The teams also assembled before the fall and spring presentations to unify and prepare ideas. Finally, several individual meetings were held to swap components and information.

2.3 PROJECT TASK ASSIGNMENTS

Following the arrangements made by previous teams, the tasks for developing the robotic arm were divided among the three participating schools. Ohio State University was in charge of developing the gripper and electronic controls. Wright State University was responsible for designing the base, lower arm, and forearm. Drawings for the completed arm components were sent to Sinclair Community College for manufacturing and assembly.



2000-2001 ARM OVERVIEW

3.1 OBJECTIVES

At the initial meeting in October 2000, representatives from both Ohio State and Wright State Universities met to discuss the project and how the design of the 2000-2001 robotic arm would be achieved. After reviewing the previous years' work on the project, the group decided on some design objectives and constraints that would make sure that the 2000-2001 robotic arm would be an improvement upon the previous designs.

The 2000-2001 design needed to be cheaper and lighter than that of Chris Fearon and the 1999-2000 team. Other improvements that were to be implemented were to increase the lift capacity of the arm and to have a fully functional control system. By the end of the meeting, the 2000-2001 team members from both universities decided on the following parameters for the new robotic manipulator:

- 6 Degrees of freedom
- Maximum weight of entire assembly less than 30 lbs.
- Fully-functional control system with working user interface
- A maximum linkage movement speed of 0.5 m/s
- Lift a 1.5 kg (~3.3 lb.) mass
- Maximum cost of \$4000 including the controls

3.2 DESIGN CONSTRAINTS

Due to the physical layout of the wheelchair, many constraints had to be placed on the design to ensure that no clearance or interaction problems would occur. The first constraint placed on the design was that no part of the assembly could extend more than 6 inches beyond the furthest edge of the wheelchair (see Figure 3.1). This constraint was placed to make sure that with the arm mounted on the wheelchair, the wheelchair would still be able to fit through a standard doorway without too much difficulty. Another constraint was that in the home position (see Figure 3.2), the arm was not taller than and does not interfere with the armrest of the

wheelchair or with the rear tire. The placement of the robotic arm was also limited by a cross member of the frame of the wheelchair. This cross member had to be taken into consideration when selecting the placement and mounting widths of the mounting brackets. The final constraint of the design was that no part of the assembly would interfere with the swivel and rotation of the front tire. This constrained the mounting height of the arm and extension of any parts below the base of the arm.

3.3 CONFIGURATION

Figures 3.1-3.4 show some different orientations of the completed 2000-2001 robotic arm.

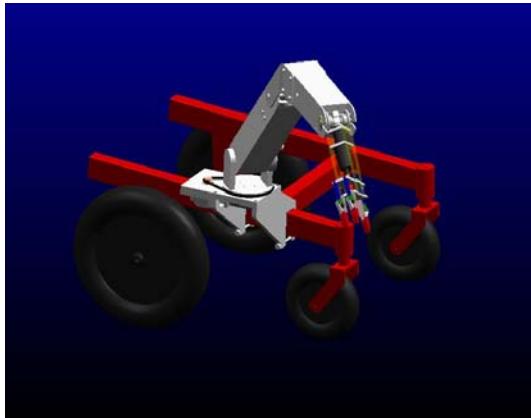


Figure 3.1 - Arm mounted on Wheelchair Frame

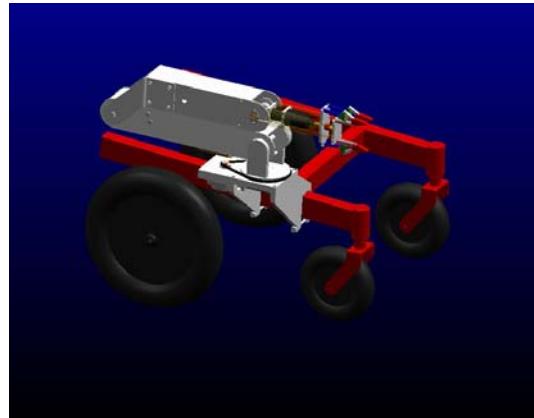


Figure 3.2 - Home Position

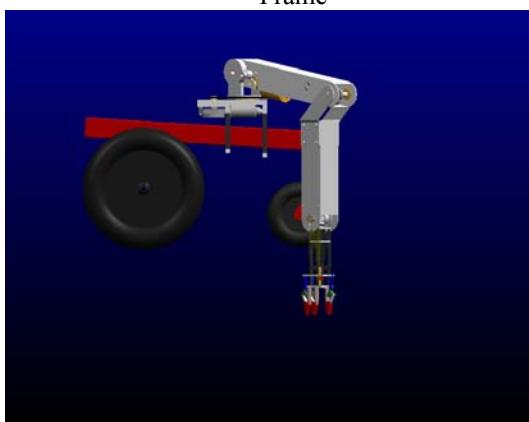


Figure 3.3 - Reaching below the Floor

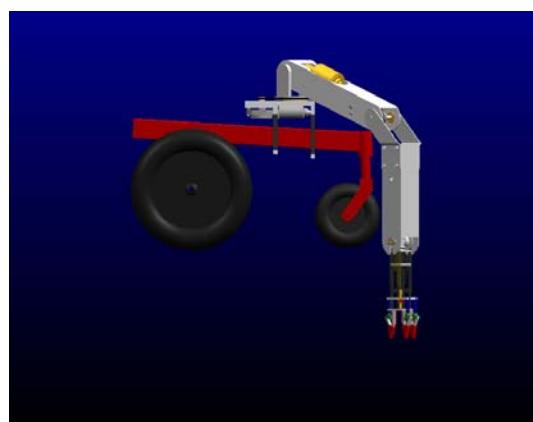


Figure 3.4 - Same Position but Different Orientation

3.4 TERMINOLOGY

Early in the project, it was realized that describing the different motions, parts, and joints of the arm was difficult. Therefore, members of both teams decided to create a standard terminology in order to make communication easier and less confusing. The basis of the

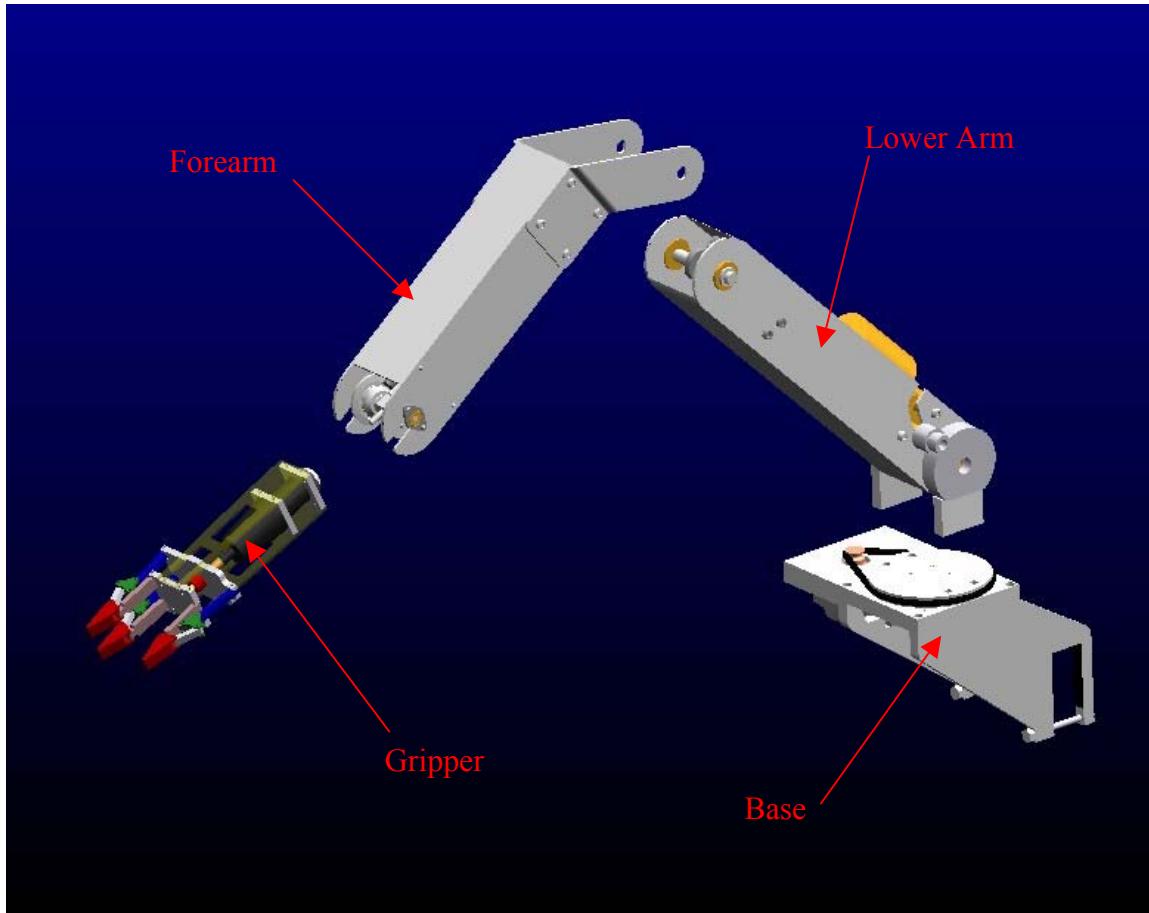


Figure 3.5 - Exploded View of Arm

terminology was the human arm. The main parts of the arm were chosen as the base, lower arm, forearm, and the gripper (see Figure 3.5). The joints were defined as they would be on the human arm, shoulder, elbow, and wrist. The shoulder is the joint between the base and the lower arm. The elbow is the joint between the lower arm and forearm. Finally, the wrist is between the forearm and the gripper. Since these three joints account for 5 of the 6 degrees of freedom, the motion of each of the joints were added to the terminology. The shoulder joint was broken into the shoulder twist and the shoulder bend motions (see Figure 3.6). The shoulder twist is the motion of the arm rotating around a vertical axis as viewed from the side of the chair. The shoulder bend is therefore the motion of the lower arm rotating around a horizontal axis. Since

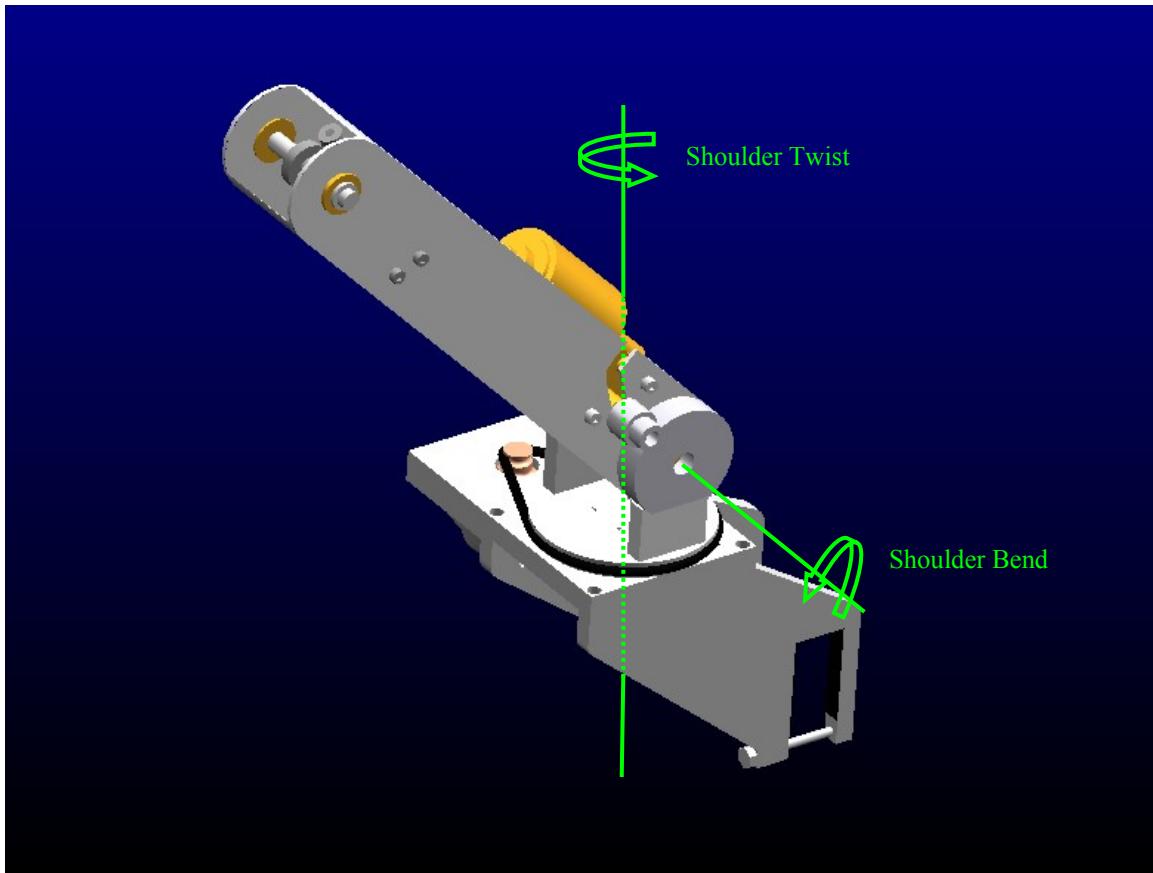


Figure 3.6 - Shoulder Twist and Bend

the elbow only has one degree of freedom, its motion was simply defined as the elbow bend. (See Figure 3.7) The wrist, like the shoulder, has two degrees of freedom. (See Figure 3.8) The wrist bend motion refers to the rotation of the gripper around an axis that is located at the end of the forearm and runs along the width of the forearm tube. The wrist twist motion is the rotation of the gripper about an axis that runs along the length of the forearm. The sixth degree of freedom is the clamping action of the gripper and is referred to as the gripping motion.

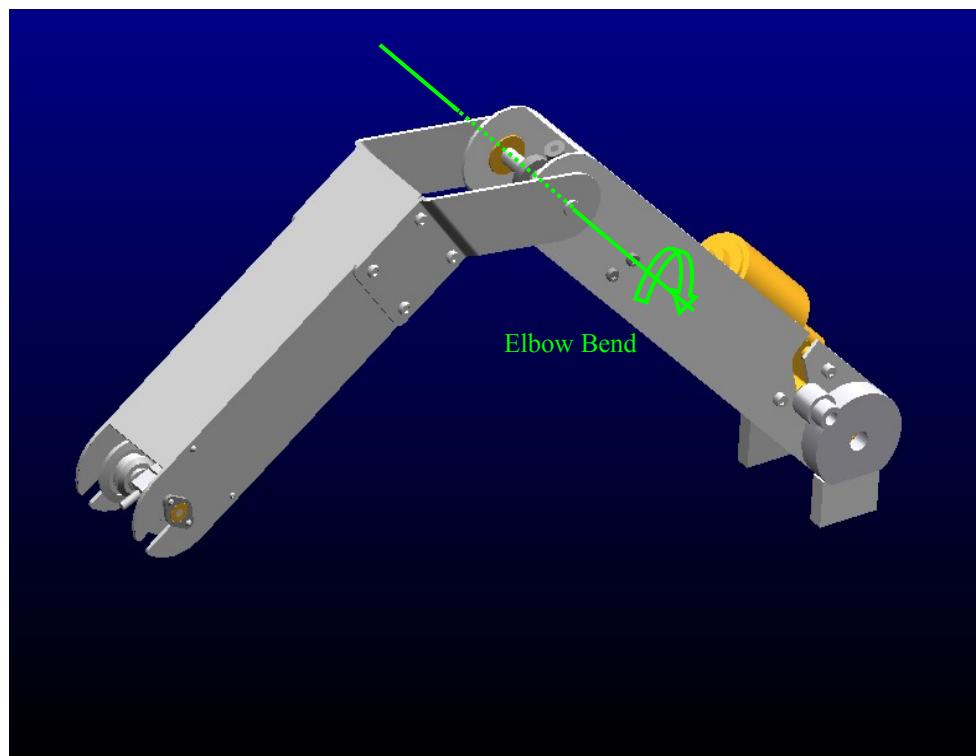


Figure 3.7 - Elbow Bend

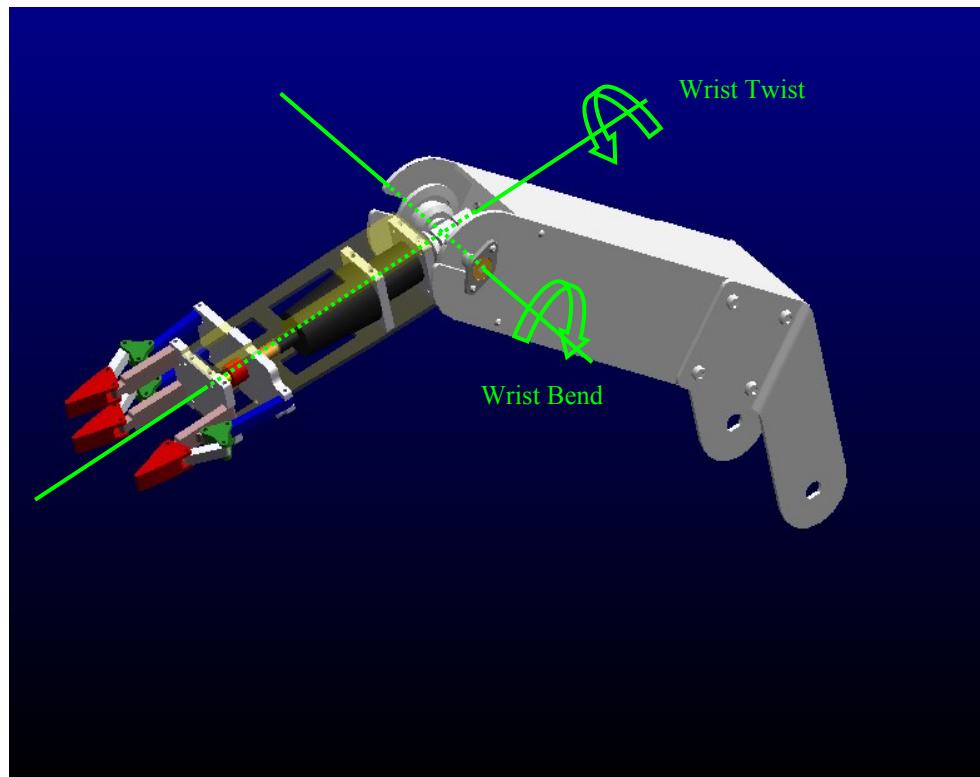


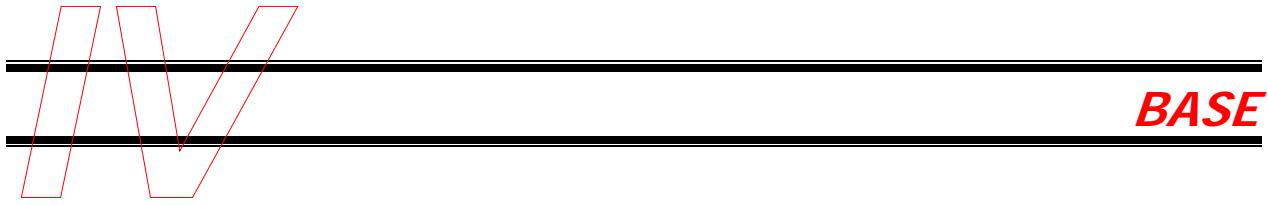
Figure 3.8 - Wrist Twist and Bend

3.5 PERFORMANCE HIGHLIGHTS

The final design of the 2000-2001 robotic arm has the following performance and functional characteristics:

- Freedom of Motion
 - Shoulder twist = 360^0
 - Shoulder bend = 210^0 max.
 - Elbow bend = 255^0
 - Wrist twist = 360^0
 - Wrist bend = 140^0
- Length
 - Shoulder to Elbow = 15.5 in.
 - Elbow to Wrist = 14.56 in.
 - Wrist to Finger Tips (open) = 11.05 in.
 - Full Extension = 41.11 in.
- Width
 - Extension beyond the wheelchair width = 3.25 in.
 - Wheelchair width with the arm = 27.75 in.
- Vertical Reach
 - Above the ground = 61.50 in. max.
 - Below the ground (plane wheelchair is sitting on) = 10.25 in. max.
- Horizontal Reach
 - Extension from front wheel of the wheelchair = 38.11
 - Extension from side of the wheelchair frame = 45.11
- Total Weight
 - 22 lbs.
- Lift Capacity
 - 3+ lbs.

The above values are actual values measured from the final arm once it was completely assembled and mounted on the wheelchair. The design criteria, as mentioned before, were not only met, but also exceeded in some areas.



4.1 MOUNTING BRACKETS

Due to the limitation in mounting positions and the structural stability of the frame of the wheelchair, it was decided that the arm would once again be mounted to the right side of the frame of the wheelchair. The frame is a rectangular cross-sectional beam that runs from the front to the back of the wheelchair (see Figure 3.1). This provides for a strong mounting position between the front and rear tires of the wheelchair. The only limitations that needed to be considered with this mounting location were clearance of the front and rear tires, location of the cross beam of the frame, and height to the wheelchair arm rest.

The brackets (see Figure 4.1) are custom machined plates of aluminum that fit over the frame. Rubber inserts are attached to the inside of the bracket cutouts and are the only parts of the entire arm assembly that contact the wheelchair. The selection of the size of the mounting bracket cutouts is such that when the rubber inserts are added, the brackets fit snuggly around the frame. The cutouts in the bracket are also deeper than the height of the tubing so a bolt can be placed through the bottom of the bracket. This bolt can be tightened to squeeze the mounting brackets around the frame of the chair and secure the entire arm to the wheelchair.

Two of these mounting brackets are used to mount the arm to the frame. Both are bolted to the stationary plate (discussed in the next section) of the arm and clamped to the frame of the wheelchair (see Figure 4.2). There is a small difference in the two mounting brackets. Since the frame of the wheelchair is not parallel to the ground, the front mounting bracket was designed to

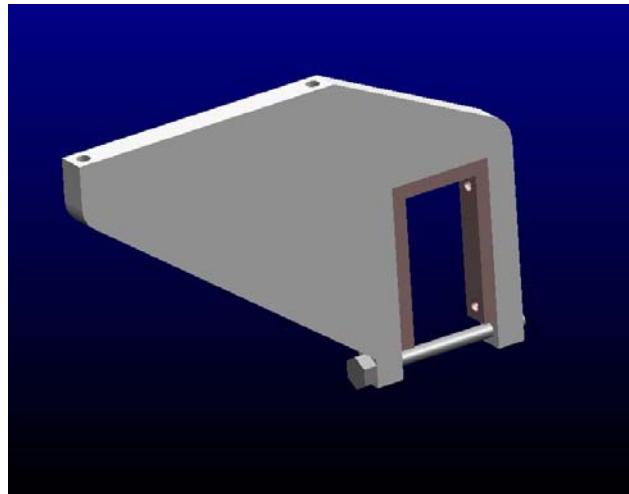


Figure 4.1 - Rear Mounting Bracket

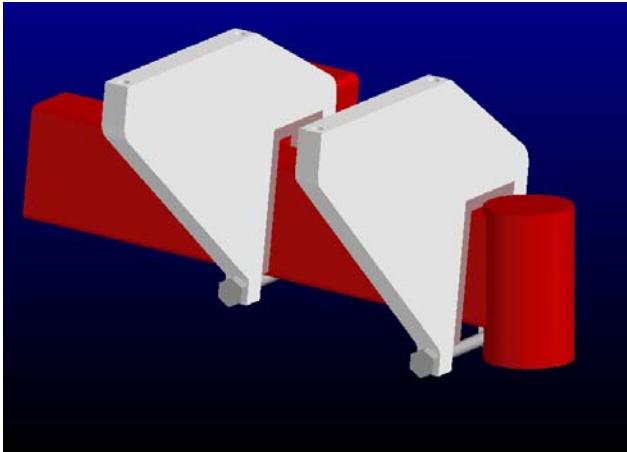


Figure 4.2 - Front and Rear Mounting Brackets

person inserts and tightens the squeeze bolts in each of the mounting brackets. Another improvement is the addition of the rubber inserts between the brackets and the frame. The rubber not only helps clamp the arm to the frame, but also protects the frame from scratching during installation and removal. The rubber also eliminates the metal-to-metal noise while the wheelchair is in motion.

be slightly taller than the rear bracket. This difference ensures that the stationary plate of the arm is parallel to the ground.

This type of clamp design offers several improvements over last year's design. The first improvement is that one person can mount the entire arm. The tight fit of the mounting brackets around the frame allows someone to slide the arm onto the wheelchair, and the arm will stay in position while the

4.2 BASEPLATE DESIGN

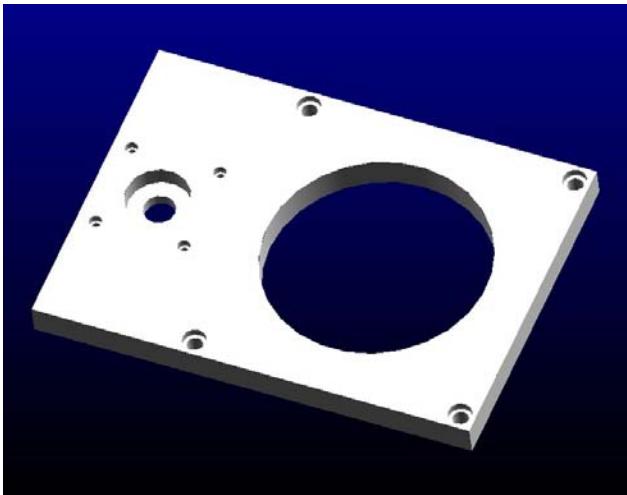


Figure 4.3 - Stationary Plate

The governing characteristic to the design of the base of the arm assembly was the limitation of width. As stated previously, the arm assembly was not to increase the width of the chair by more than six inches. Since the stationary plate was the part that extends the farthest from the wheelchair, the width of the stationary plate was the limiting factor in its design.

Initial brainstorming and discussion led to the decision that both the twist and the bend motors of the arm should be mounted in the base of the arm to save weight in the lower arm. With this in mind, initially the stationary plate and corresponding components were designed to accommodate both motors in the base.

The initial design of the stationary plate was a 0.50-inch thick piece of aluminum that measured 5.00 x 7.00 inches (see Figure 4.3). The large 3.50-inch diameter hole in the plate was for the placement of the twist bearing, and the smaller 1.00-inch diameter cutout supports the bearing for the twist motor shaft. An 18-volt Black and Decker Firestorm cordless drill motor was selected for both the twist and bend motions of the arm. The twist motor was mounted directly to the bottom of the stationary plate in a vertical orientation (see Figure 4.4). The drive gear for the twist motion was linked to the motor by a 0.4375-inch shaft supported by the aforementioned bearing. The drive gear was a 2.00 diameter simple spur gear that had a face width of 0.3125 inches. Rotational motion was transferred to the large twist gear via the drive gear.

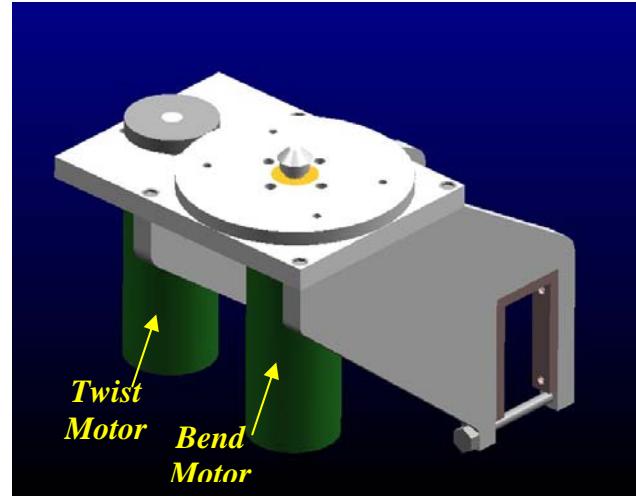


Figure 4.4 - Complete Base with Motors

The large twist gear was a major component in the operation of the arm. The gear was a 5.00-inch diameter spur gear with a 0.3125-inch face width. The diameter was limited to 5.00 inches because of the width of the stationary plate. A larger diameter gear would hang over the edges of the plate and cause operational and safety issues. The importance of the twist gear was that the rest of the arm was mounted to it. The shoulder mounting brackets would sit on top of the twist gear and be bolted from the bottom of the gear.

Attached to the bottom of the twist gear was the shoulder motor assembly (see Figure 4.5). This assembly consisted of a spacer, motor mounting plate and motor. The 0.75-inch

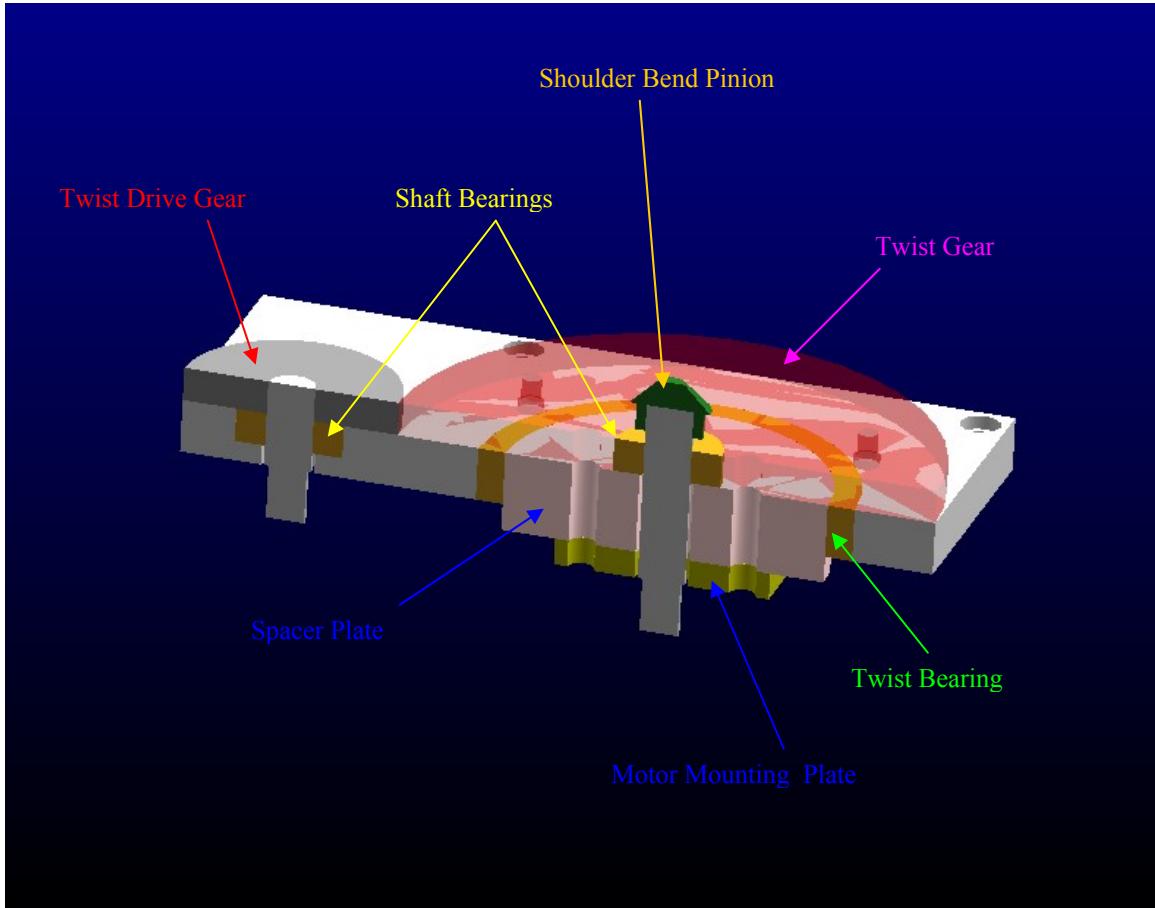


Figure 4.5 - Cutaway of Stationary Plate and Bearing Assembly

aluminum spacer was to sit inside the twist bearing and support all of the moment experienced by the joint. A 0.25-inch plate, which served as a mounting plate for the motor, was located at the bottom of the of the spacer plate. The motor was bolted to this plate in a vertical position. This design allowed the shoulder bend motor to twist with the rest of the arm.

To bend the shoulder joint, holes were to be machined through the centers of the spacer and mounting plate so that a 0.4375-inch shaft could be run from the shoulder motor up to the shoulder joint. A 1.00-inch OD bearing was placed in the center of the twist gear to support the shaft but also allow it to rotate independently of the twist gear. A 0.75-inch beveled gear was used to drive the bend of the shoulder. This beveled pinion drove a 2.00-inch bevel gear, which was fitted to a 0.50-inch diameter shoulder shaft, which was supported by 1.00-inch diameter

bearings mounted inside the shoulder mounting brackets. The shoulder shaft was also connected to the lower arm tubing, which was placed between the shoulder mounting brackets, and was held in position by snap-rings on each end.

As previously mentioned, both the twist and bend motions were to be driven by the same type of motor. The common use of motors allowed for a lower overall cost, fewer part numbers, and easier repairs. The Firestorm drill motor applies enough torque that after a small amount of gearing, the torque applied at the shoulder for the bend motion would easily meet the nearly 500 in-lbs required to move the arm under maximum loading conditions. The torque needed to twist the arm is more than enough to over come the friction of the bearings, which is easily done by the motor even before gear reduction. The Firestorm also operates at a fairly low rpm so that gearing can slow the rotation of each of the two motions to a manageable speed. One problem with the Firestorm drill motors is that even though the gearing can slow down the operation of each of the two joints, they will still be much faster than the targeted 5 rpm speed (~0.5m/s linkage speed).

The gearing ratios selected were governed by space limitations of the base and shoulder joint. The twist gearing was 2.5:1 and the bend gearing was 8:3. These gear ratios were chosen to produce the largest torques and the slowest rotational speed without changing the configuration and design of the rest of the components. For example, the bevel gear in the shoulder could not be any larger without interfering with the lower arm tubing, and the shoulder pinion could not be any smaller because of the size of the motor shaft it is attached to.

Further investigation into electric motors led to the acquisition of less expensive, more



Figure 4.6 - Shoulder twist motor

powerful, and slower motors that better suited our arm than the previously selected Firestorm motors. This change in motor selection required an immediate and extensive redesign of the base of the arm. The new twist motor is a window lift motor (see Figure 4.6), and the new bend motor is a high torque, low rpm motor. Due to the size and orientation of the new bend motor, it could no longer be mounted in the base and was moved to the lower arm. The twist motor is still in the base

but numerous changes have been made.

The new stationary plate has been extended to be 5.00 x 8.00 inches and no longer has a uniform thickness (see Figures 4.7 and 4.8). To mount the twist motor under the stationary plate length-wise, the plate is 0.85 inches thick at one end and 0.625 inches at the other. This



Figure 4.7 - New Stationary Plate

mounting configuration is also why the stationary plate had to be extended out to 8.00 inches. The change is so that the motor will fit tightly against the bottom of the plate and a minimum amount of weight would be added to the base. A 3.5-inch diameter circle is cut 0.5625 inches deep for the placement of the twist bearing assembly. Also, a 1.125-inch diameter hole is cut to allow clearance for the new twist drive pulley. A 4.00 x 4.00-inch square area concentric with the bearing cutout is

cut 0.125 inches deep so a bearing retaining plate can be mounted flush to the top of the stationary plate.

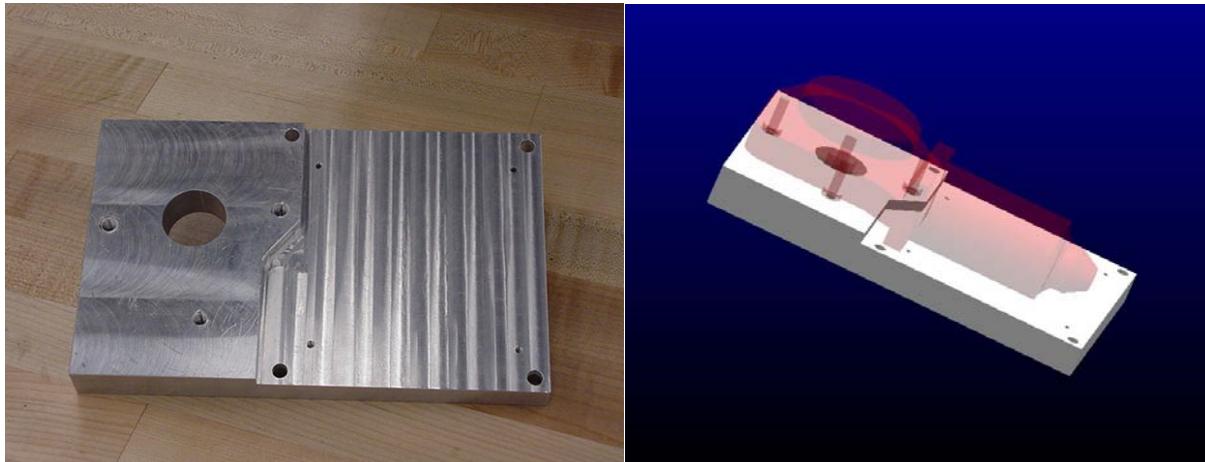


Figure 4.8 - Bottom of Stationary Plate with and without the Twist Motor

Orienting the motor across the bottom of the plate and having two different thicknesses required a change in the rear mounting bracket also (see Figure 4.9). The placement of the rear bracket is still the same and so are the majority of the dimensions, except now the rear bracket has to go around the motor. Therefore, a cutout was made to the old design (see Figure 4.9) to make sure the mounting bracket would fit around the motor. Also, the step on the bottom of the

stationary plate causes the two places where the rear mounting bracket is bolted to the plate to be at different locations. This meant that one side had to be shortened to ensure that the fit was correct.

A new rubber insert was also selected for the mounting brackets. The new insert is thinner and can be attached by adhesive. This change makes the machining of the brackets less expensive since the tapped holes are eliminated from the cutout where the rubber inserts are placed. The thinner inserts changed the cutout dimensions slightly but not extensively.

The front mounting bracket was not affected by the new motor or change in the stationary plate. The only changes to the initial design of the front mounting bracket was the elimination of the tapped holes for the rubber insert and the dimensional changes for the cutout where the insert is placed.

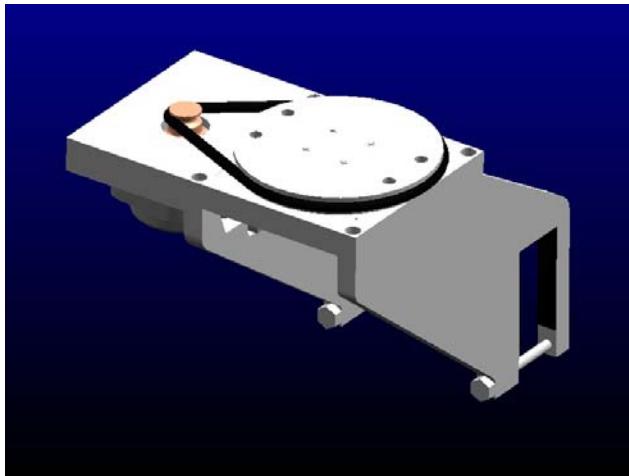


Figure 4.10 - New Base Assembly

prevent people from getting hurt by inadvertently twisting the arm into a person standing close to the wheelchair.

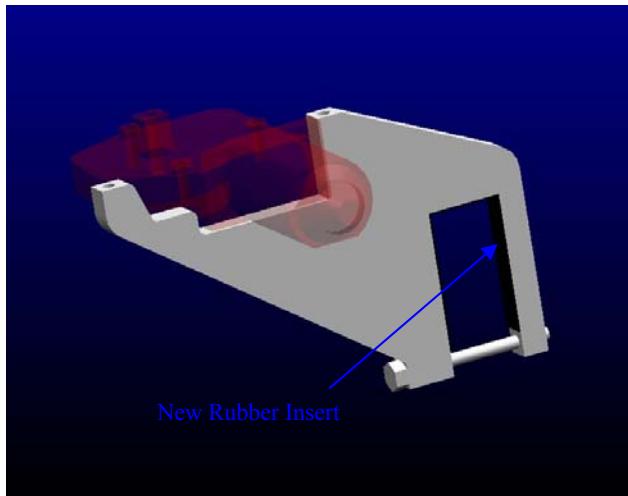


Figure 4.9 - New Rear Mounting Bracket with Twist Motor

The new twist motion utilizes a belt and pulley system instead of gears (see Figure 4.10). This change was made because the new motor moved the center of the motor shaft further from the center of the bearing hole. A benefit of this change is the pulley also acts as a safety device. The pulley will slip and prevent the motor from burning up if the arm is constrained from twisting for any reason. This limitation on the twist torque may also

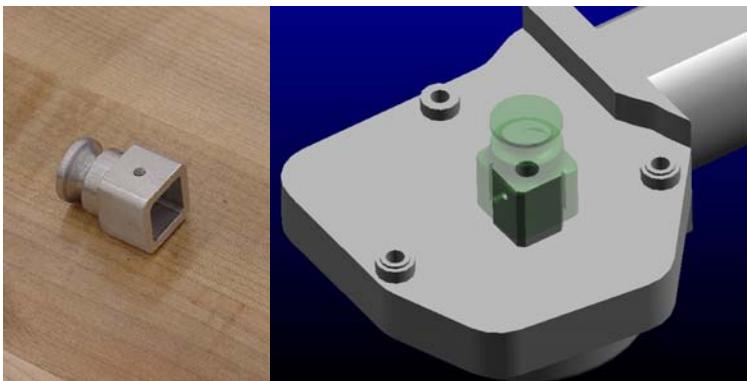


Figure 4.11 - Drive Pulley

The drive pulley is a very intricate piece that is machined from solid aluminum (see Figure 4.11). The lower side of the pulley is designed to slide over the existing 0.562-inch square drive of the twist motor and is held in place by a setscrew. The upper section is a 0.75-inch diameter cylinder with a 0.125-inch radius groove cut around it. The groove creates a 4.50-inch diameter pulley that accepts a 0.25-inch diameter belt.

The twist pulley (see Figure 4.12) is similar to the twist gear originally designed in that it still supports the shoulder mounting brackets and therefore the rest of the arm. The pulley is a 4.75-inch diameter circular plate of aluminum that is 0.4275 inches thick. A 0.125-inch radius groove is cut around it to create a 4.50-inch diameter pulley that accepts a 0.25-inch diameter belt. Since the bend motor is now in the lower arm, the hole for the bearing and motor shaft have been eliminated. The twist pulley is mounted to the center twist bearing piece, which is part of a 3-piece bearing design and will be discussed later.

The twist belt is a black neoprene belt with a round cross-section. The diameter of the cross-section of the belt is 0.25 inches and thus matches the grooves in the two pulleys. The belt has a length of 399 mm.

This redesign accommodates the twist motor and also improves upon the first design in a number of ways. The use of the pulleys not only acts as a safety device, but they are also cheaper than the gear design used initially. These pulleys are easily machined from stock aluminum and do not have to be specially ordered. The new design also has a more desirable gearing ratio for the twist motion. The pulleys produce a speed ratio of 9:1. This ratio produces



Figure 4.12 - Twist Pulley

more torque to overcome the friction in the bearings and also slows the rotational speed considerably.

The initial bearing design was 0.50-inch thick bearing. The outer diameter was 3.50 inches, and the inner diameter was 3.00 inches. This is a very simple and effective design. The choice of material was that of oil impregnated brass because of its wear and frictional characteristics. This was an improvement upon the previous year's design because it was cheaper and reduced the material required.

The redesign of the base also brought about a redesign of the twist bearing. A three-piece bearing assembly was designed to take the place of the single bearing (see Figure 4.13 and 4.14). The main piece of the assembly is the center bearing. This piece is bolted to the twist pulley from the top and is the only moving component in the bearing assembly. The lower part of the

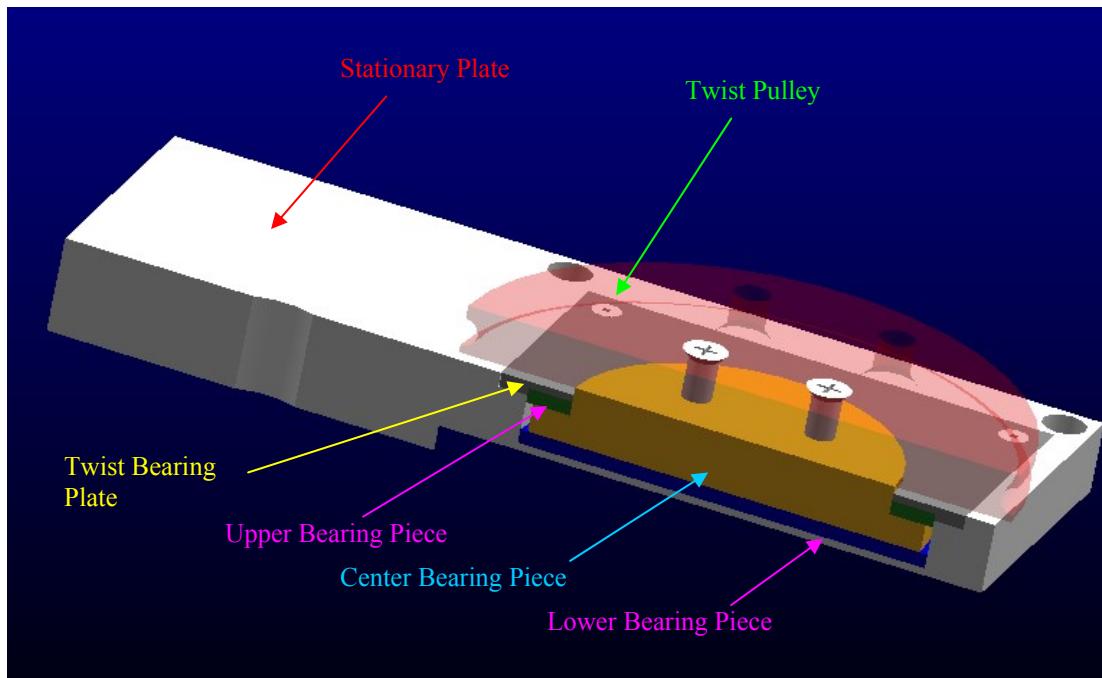


Figure 4.13 - Cutaway of New Twist Bearing Assembly

bearing has a diameter of 3.375 inches. This is slightly smaller than the hole in the stationary plate where it is placed so that it can rotate freely without contacting the stationary plate. The upper section of the center bearing piece has a 2.75-inch diameter. This part extends up through the center of the upper bearing piece and the bearing plate. This is the end that is bolted to the twist pulley.

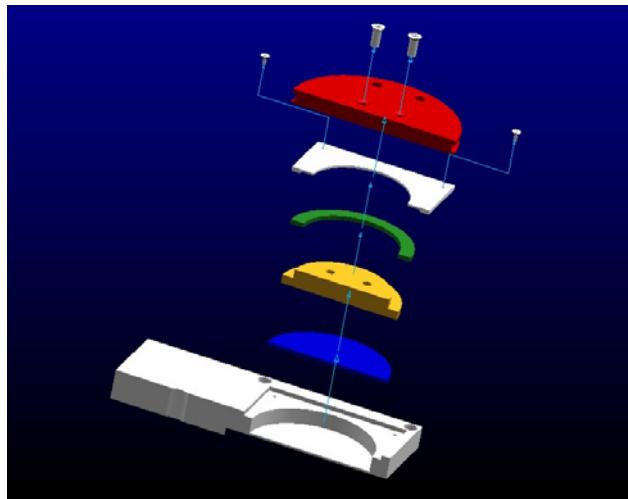


Figure 4.14 - Cutaway and Exploded View of Bearing Assembly

The other two parts of the bearing assembly are very similar and only have one difference. Both are 0.125 inch thick and have a diameter of 3.50 inches. The difference is that the upper bearing piece has a 2.75 inch diameter hole cut through it. Both pieces are pressed into the stationary plate and do not rotate. The lower piece goes under the center piece, and the upper piece fits around the upper section of the center bearing piece.

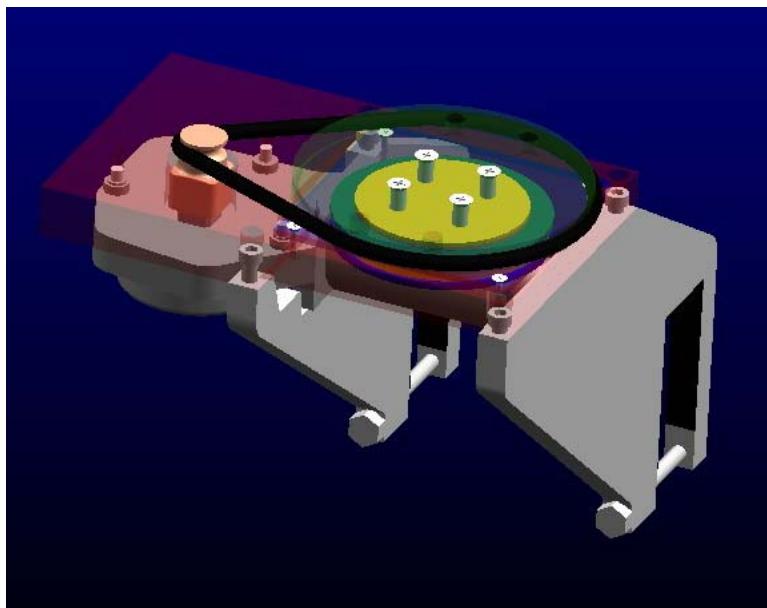


Figure 4.15 - Complete Redesign Base Assembly

piece against the upper piece, and the OD of the upper section of the center piece against the ID of the upper piece.

All three pieces of the twist bearing assembly are made of oil impregnated nylon. Nylon was chosen over brass due to its availability and lower cost. The bearing assembly is designed such that all points of friction are nylon against nylon. The nylon-to-nylon decision was made to try and minimize wear and noise. These contact areas are the entire bottom of the center piece against the lower piece, the ledge of the center

The bearing assembly is held in place by a bearing plate. This 4.00 inch square plate bolts to the stationary plate in the previously described cutout and holds the bearing assembly in the stationary plate.

The final base assembly is shown in Figure 4.15 with the stationary plate, twist pulley, and twist bearing plate all transparent so that the rest of the components can be seen. Finally, an exploded view is shown in Figure 4.16. This shows each component of the redesigned base assembly and how they are assembled.

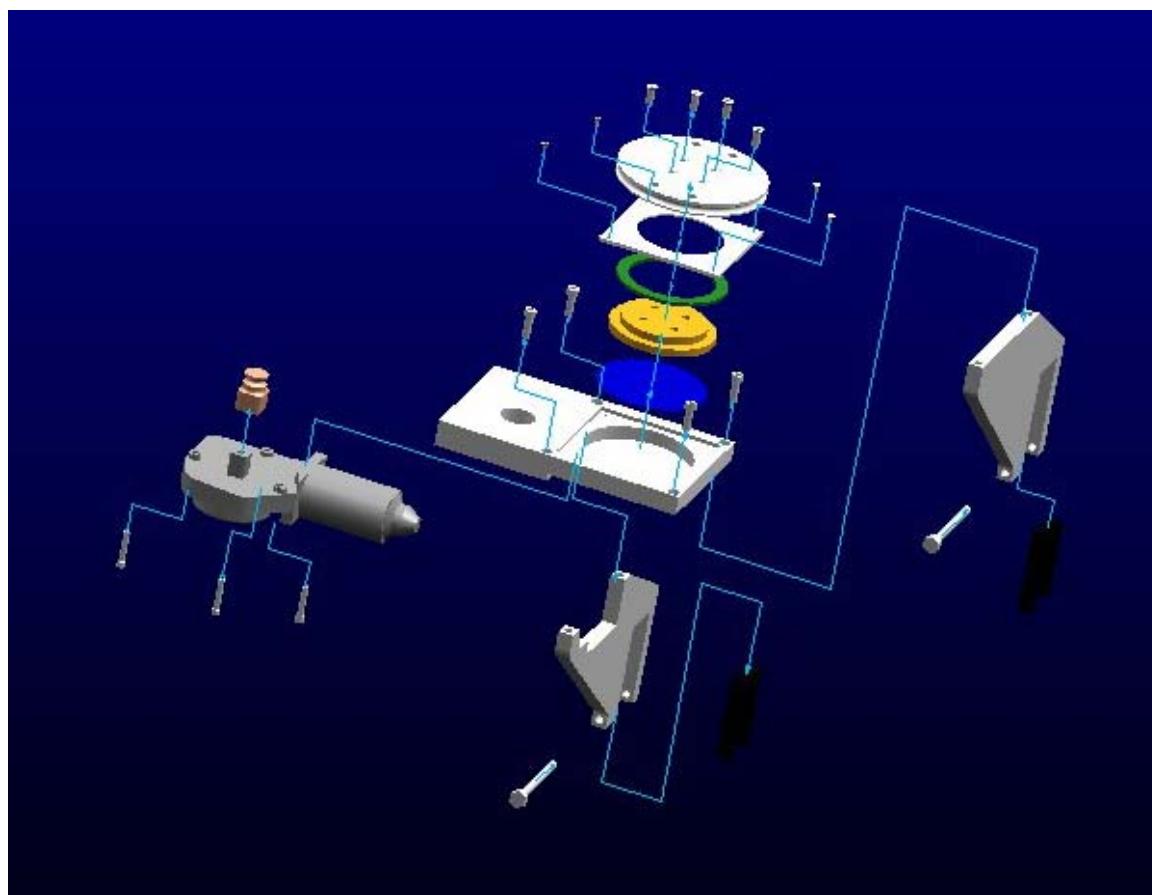
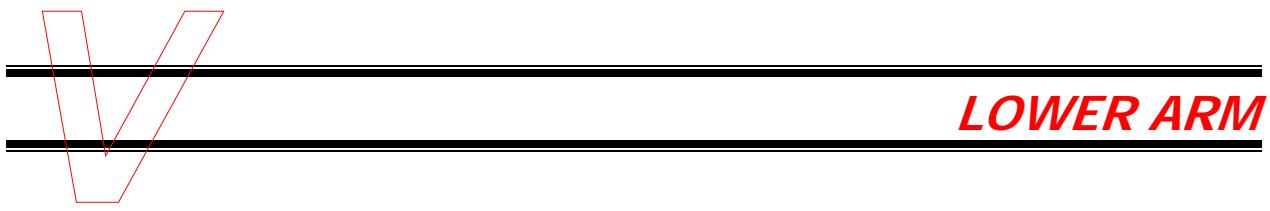


Figure 4.16 - Exploded View of Base Assembly



5.1 SHOULDER JOINT

The shoulder joint was of primary importance in the design of our robotic arm. Due to the weight of the arm and its overall length, the imposing moment on this joint is substantial. Preliminary calculations estimated this moment to be 483 lb-in. This meant that all components of the shoulder joint needed to be designed to support this load. This was especially crucial in choosing a motor to power the bending motion at this joint.

During early brainstorming sessions, the thought of using cordless drill motors for high torque joints seemed feasible. Upon testing, however, it was apparent that excessive gearing

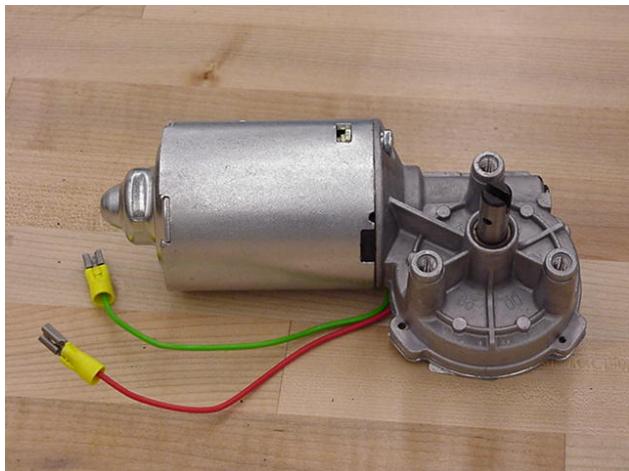


Figure 5.1 - Shoulder Bend Motor

would be required to bring the rotational speed of the motor down to a reasonable speed. It was for this reason that a gearhead motor was sought. The chosen motor is a 24V DC gearhead motor that supplies 300 lb-in of torque and rotates at a maximum speed of 33 rpm (see Figure 5.1). This motor requires very little gearing to achieve the high-torque, low-rpm goal. This motor also features a right angle gearhead, which makes transferring the

power to the shoulder joint simple, and eliminates the need for expensive bevel or miter gears.

The power from the motor is transferred through a set of spur gears to reduce the speed by a 3:1 ratio. The chosen gears were generously donated by the Boston Gear Corporation. The gears are made of steel and have a diametral pitch of 20 and a face width of 0.5 inches. The shoulder joint pinion and gear are Boston's YA20-1/2 and YA60A models respectively. The pinion has a pitch diameter of 1 inch and a bore of 0.5 inches. The gear has a pitch diameter of 3 inches and a bore of 0.5 inches.

To save space and weight in the shoulder joint, the gear was incorporated into the design of one of the mounting brackets (see Figure 5.2). In previous designs, the shoulder brackets served only to support the arm, to mount the arm to the base, and to provide a location to place the shoulder bearings. In the new design, one of the brackets also serves as part of the shoulder

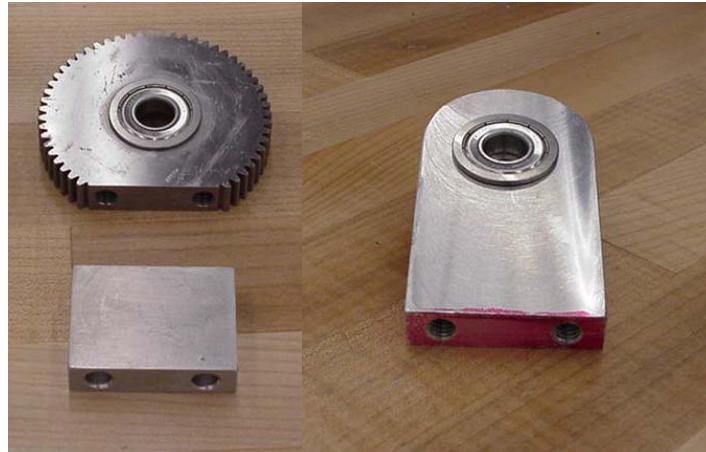


Figure 5.2 - Left and Right Shoulder Mounting Brackets

joint gearing. By modifying the shoulder gear, the new design allows the gear to accommodate a bearing for the shoulder shaft and be mounted to a small aluminum block to create a “bracket” that is equivalent in size to the previous design.

The shoulder joint bearings are model E7-S3F flanged ball bearings from PIC Design. They have an outside diameter of 1.125 inches and a bore of 0.5 inches. This accommodates the shoulder shaft perfectly. The bearings are rated much higher than they will ever be tested in practical use.

The shoulder shaft is a simple D-shape design with a diameter of 0.5 inches (see Figure 5.3). The D-shape shaft fits into a similar hole cut into one end of the lower arm tube. This effectively mounts the shaft to the lower arm so they move as a single unit. The shaft rotates in the mounting brackets by way of the shoulder bearings.

The motion of the arm is caused by

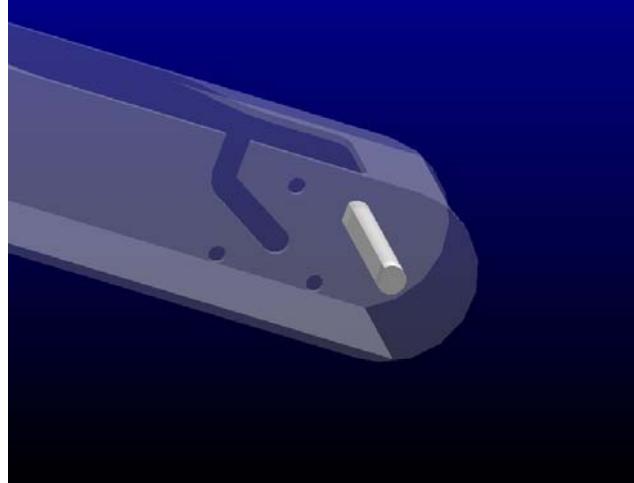


Figure 5.3 - Shoulder Shaft

the shoulder bend motor driving the shoulder pinion around the shoulder gear (see Figure 5.6).

5.2 LOWER ARM TUBE

In trying to reduce the overall weight of the robotic arm in comparison to previous designs, the structure of the lower arm was rethought and redesigned. In the 1999-2000 Gateway team design, the lower arm primarily consisted of two 0.5-inch thick aluminum plates (see Figure 5.4). Though these plates were very strong, they added an unnecessary amount of weight to the arm. By using square aluminum tubing (see Figure 5.5), we were able to keep the structural integrity of the arm while reducing the weight significantly. This design is similar to that of recent OSU graduate student Chris Fearon.



Figure 5.4 - Arm Plate from 1999-2000 Design

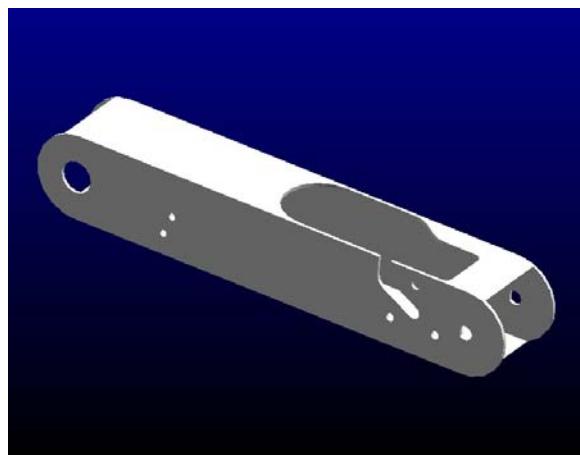


Figure 5.5 - Lower Arm Tube

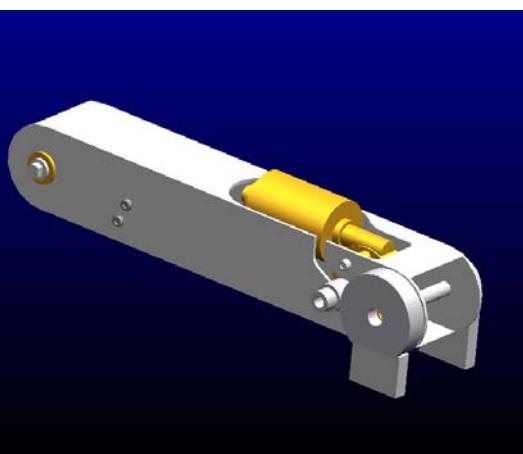
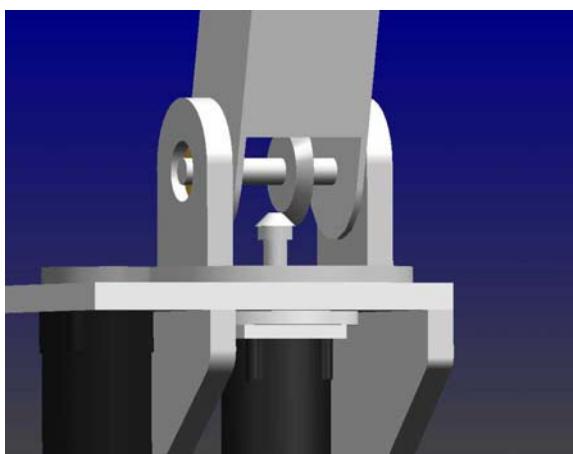


Figure 5.6 - Preliminary and Final Shoulder Joint Designs

In our preliminary design, the shoulder bend motor was attached to the base of the arm. Using a set of bevel gears, the power was transferred to the shoulder joint. This kept the weight of the motor off the arm, thereby reducing the required torque to rotate the shoulder joint. Upon changing the motor for this application, this mounting position was no longer feasible for the shoulder bend motor due to space limitations. The solution was to house the motor in the lower arm tube and transfer power to the joint using a pair of spur gears. Although this position adds to the necessary motor torque, it also reduces the cost of gearing significantly over the initial design.

The large size of the motor chosen to power the bending motion at the shoulder joint required the lower arm tube to be machined extensively. Since the motor could not be placed inside the tubing completely, a large contoured hole was machined out of the tube to accommodate the protruding parts of the motor. To provide for easy servicing, a slot was cut into the tubing to allow the motor to be slid into place and bolted securely. This allows for easy assembly and service of the shoulder motor and joint (see Figure 5.7).

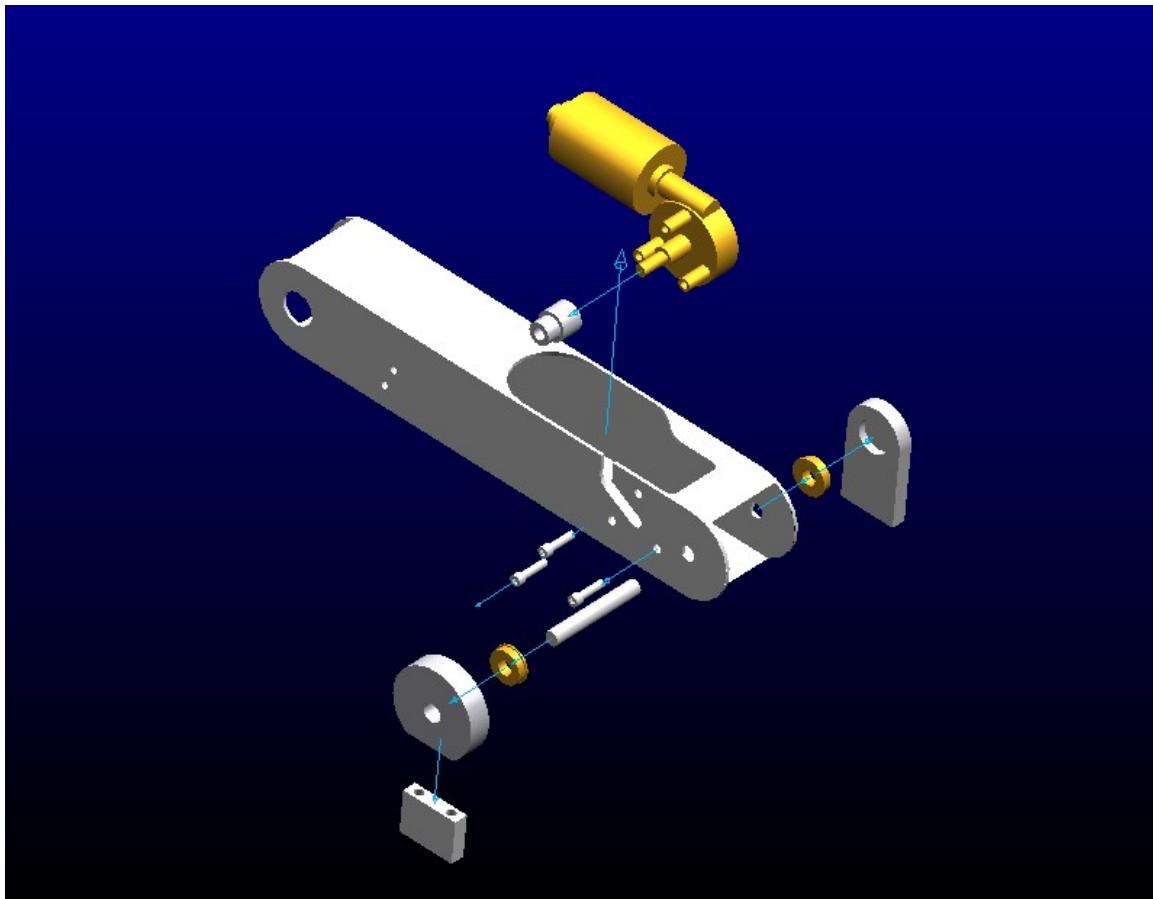


Figure 5.7 - Exploded View of Shoulder Joint

5.3 ELBOW MOTOR

The motor initially selected for the elbow joint was the 18-volt Black & Decker Firestorm drill motor, the same motor as originally chosen for the shoulder twist and bend motions. Ordering the same motor for all joints would decrease the difficulty of obtaining all necessary motors, but this proved not to be the best design for the robotic arm.

Combined with a controls encoder, the motor extended approximately 8 inches and weighed over 1.76 pounds. Initially, the design team sought to place the motor at the baseplate and transfer the power up to the elbow joint through transmission pulleys, minimizing torque requirements at the shoulder bend motor. However, since the motor-encoder assembly extended nearly the entire length of the lower arm tubing, the drill motor was mounted within the tubing directly aligned to the elbow joint, as seen in Figure 5.8. Bevel gears reduced the speed of the elbow rotation to below 12 rpm.

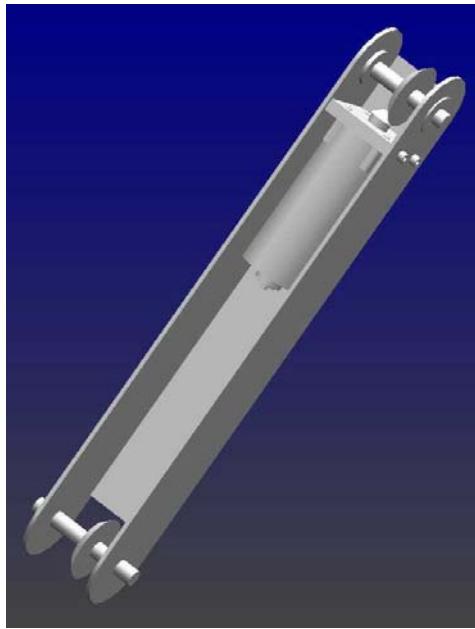


Figure 5.8 - Preliminary Elbow Motor
Without Encoder

Flanged bearings were press fit into the lower arm tube to support the elbow shaft. Outside of the bearings, snap rings were fastened to the shaft to secure it from sliding and to lock the bearings in place.

Upon further research, the motor from a Black & Decker Model 9074 3.6V cordless screwdriver was selected to replace the drill motor. The screwdriver motor was

smaller and lighter than the drill motor; the complete motor assembly weighed approximately 1 pound, reducing the motor weight by approximately 40%. However, the 3.7-inch long motor still produced 40-in-lb of torque, enough to operate the elbow. Furthermore, the screwdriver operated at a maximum of 180 rpm, thus requiring less gear reduction than the drill motor.

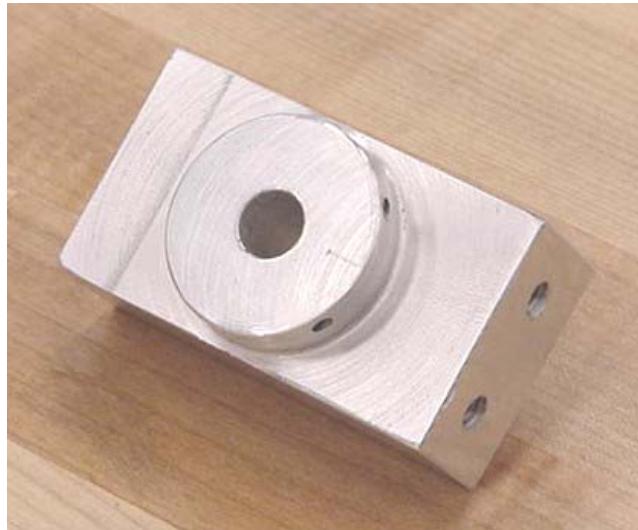


Figure 5.9 - Elbow Motor Mounting Block

The gearing for the screwdriver involved two planetary gear sets contained within a plastic chuck. To maintain the lightweight, compact internal gearing arrangement and to avoid machining additional parts, the entire chuck and gear assembly was removed from the screwdriver, mounted to a fabricated motor mounting block. The mounting block, seen in Figure 5.9, was designed to hold the gears within the chuck, properly mate the screwdriver motor to the gearing, and secure the entire drive assembly to the lower arm tubing. The block was made as thin as possible to minimize weight. Two machined retaining plates were attached to the motor mounting block to secure the motor and to prevent unwanted motor rotation, seen in Figure 5.10.

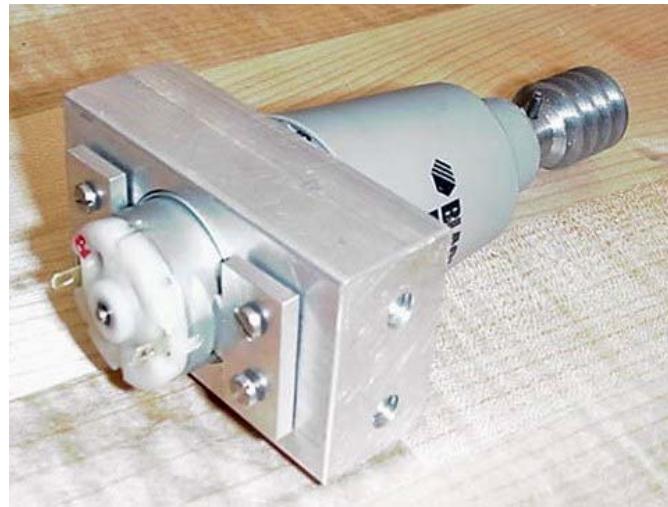


Figure 5.10 - Elbow Motor Assembly

The adapter for the screwdriver bits was removed from the press-fit clamp within the screwdriver gearing and replaced with a steel 0.25-inch diameter shaft, upon which the elbow worm was aligned and pinned. A 20:1 gear ratio was selected to drive the elbow joint. The 16-pitch, 0.625-inch diameter elbow worm was chosen from the Boston Gear catalog for its strength, small size, and bore diameter, which permitted the worm to be attached to the screwdriver motor assembly. The associated 1.25-inch pitch-diameter gear provided the necessary gearing reduction while permitting enough room for the worm/motor assembly to be completely mounted within the lower arm tubing. The assembly was mounted at a 21.53° offset from horizontal, as seen in Figure 5.11.

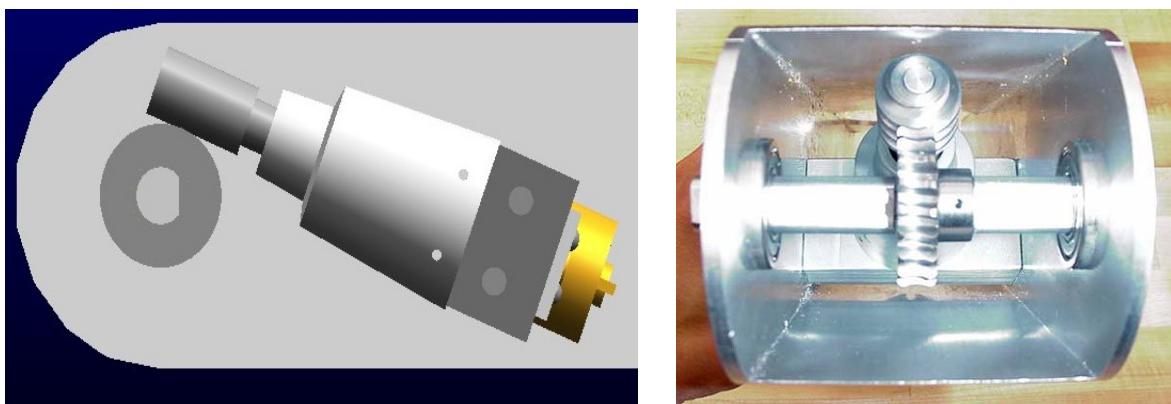


Figure 5.11 - Elbow Motor Mounted at Angle

The elbow shaft was modified both to secure the worm gear and eliminate the retaining clips. The 0.5-inch shaft was revised into two mated components each with a 0.75-inch diameter flange which, when assembled in the lower arm, were secured between the elbow bracket and elbow bearings, effectively preventing the shaft from moving laterally. The worm gear, with a 0.25-inch bore diameter, was clamped between the two elbow shaft components and pinned upon the male member. The entire shaft and gear assembly is seen in Figure 5.11 and 5.12.

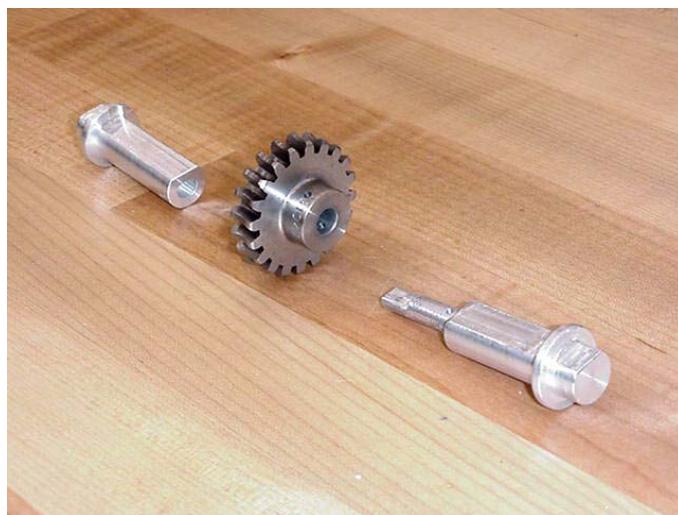


Figure 5.12 - Elbow Shaft and Gear Assembly

D. Elbow Brackets

Connecting the forearm and the lower arm are two 0.125-inch-thick aluminum elbow brackets. Incorporating a 135-degree bend, the brackets significantly increase the range of rotational motion of the forearm. Combined with mounting the brackets on the outside of the aluminum tubing, bracket design increases rotational motion from 180 degrees in the 1999-2000 undergraduate students' and 2000 graduate student's designs to 255 degrees. The angle also allows the forearm to rest directly atop the lower arm, permitting the entire arm to fold into a compact rest position. Each bracket includes a jog to accommodate the flanges from the elbow shaft.



Figure 5.13 - 2000 Graduate
Student Elbow Bracket

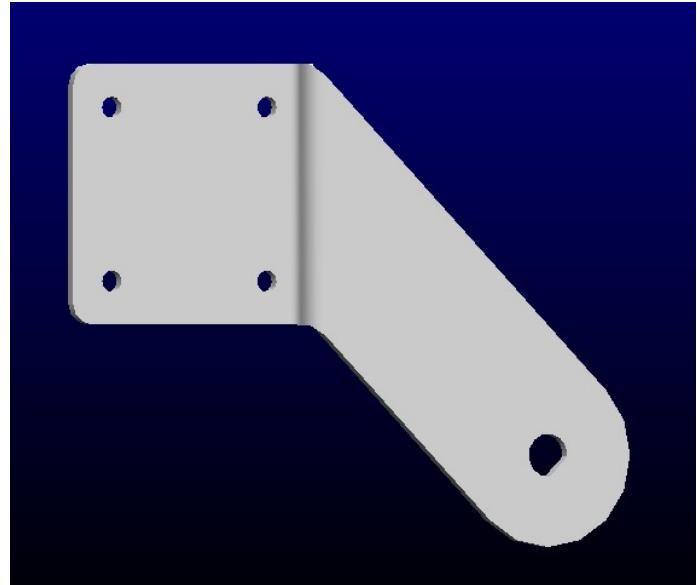
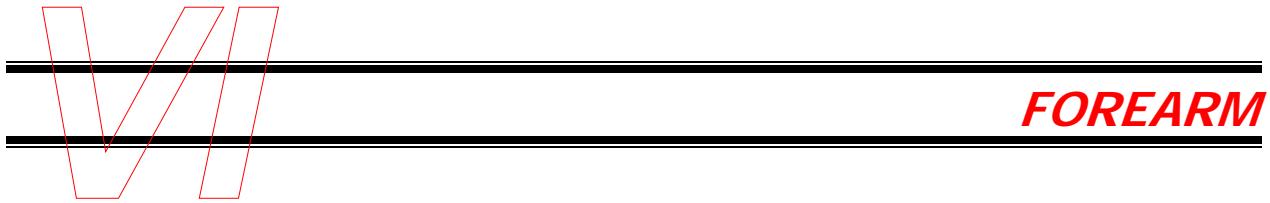


Figure 5.14 - 2001 Elbow Bracket



6.1 FOREARM TUBING

The forearm design was closely modeled after the 2000 graduate student design, once again incorporating the square aluminum tubing. The tubing with a 1/8-inch wall thickness provides a compact, lightweight supporting structure that completely encloses all forearm components, protecting both the equipment as well as the user from potential injury.

The preliminary design employed a 2.5-inch square tube, similar to the preliminary tube used in the lower arm. Uniform tubes reduced the costs for obtaining raw materials and permitted a compact rest position for the arm. The tubing supported two mounting plates, which secured the motors driving the differential gears at the wrist. Seen in Figure 6.1, one motor was offset behind the other motor, permitting both to fit within the enclosed tube. An aluminum drive shaft, supported by a bearing, connected the offset motor to its differential gear, while the pinion from the other motor was mated directly to its respective gear.

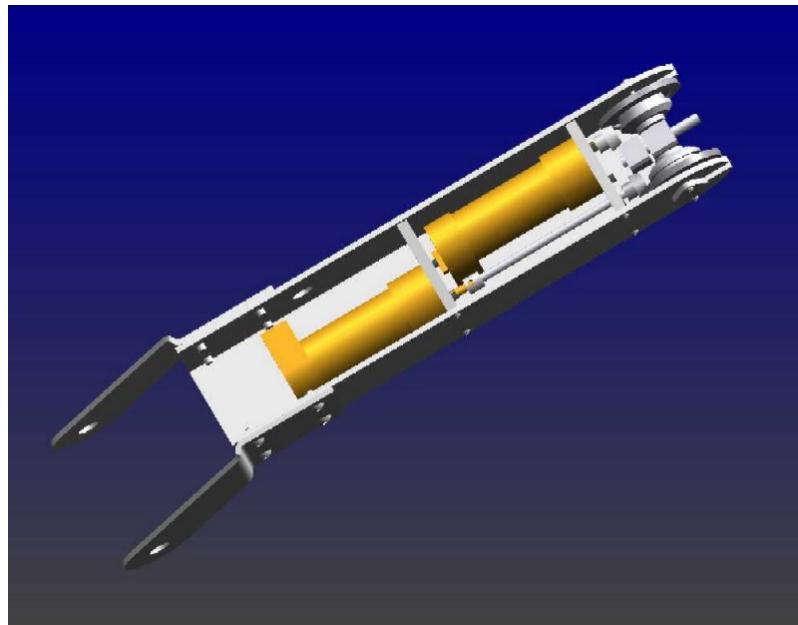


Figure 6.1 - Preliminary Forearm Tubing with Offset Wrist Motors

When the lower arm tubing was expanded for the final design to accommodate new motors and because the 2.5-inch square tubing was expensive and difficult to obtain, the forearm tubing was also enlarged to maintain uniformity. The 3.0-inch square tubing, which is readily available, was chosen in place of the 2.5-inch square tube. The 3-inch tubing permits the two wrist motors to be placed next to each other, eliminating the need for a second motor mounting plate, bearing, and drive shaft. Figure 6.2 illustrates the parallel position of the wrist motors. Fewer components within the forearm reduced not only materials and machining costs but also the overall weight of the design.

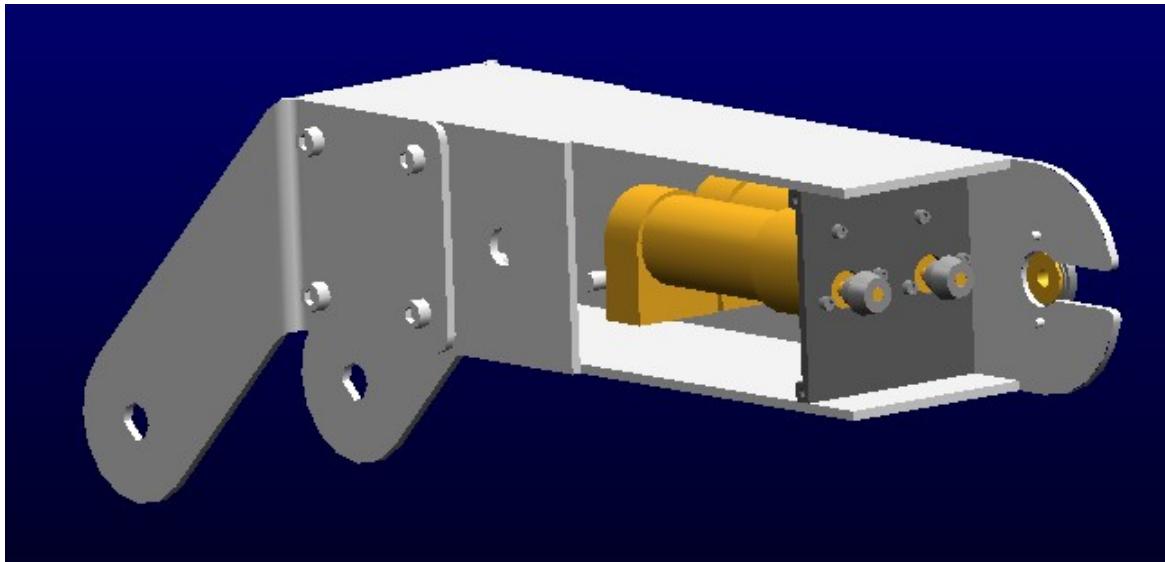


Figure 6.2 - Final Forearm Tubing with Parallel Wrist Motors

Two oil-lubricated ball bearings are press-fit into two wrist pillow blocks, machined from 0.25-inch aluminum plate, and attached to the forearm tubing to support the wrist differential. The bearings and wrist pillow blocks can be seen in Figure 6.3.



Figure 6.3 – Wrist Pillow Block and Bearing

6.2 WRIST DIFFERENTIAL

The wrist twist and bend motions are controlled by a differential gear set identical to the gearing on the 1999-2000 undergraduate students and the 2000 graduate student designs. The bevel-gear configuration provides two degrees of freedom within a compact volume.

In the final design, placing the wrist motors side-by-side increased the distance between the motor shafts. Spacers, appearing as red in Figure 6.4, were fastened between the differential and the outer bevel gears to accommodate the repositioning.

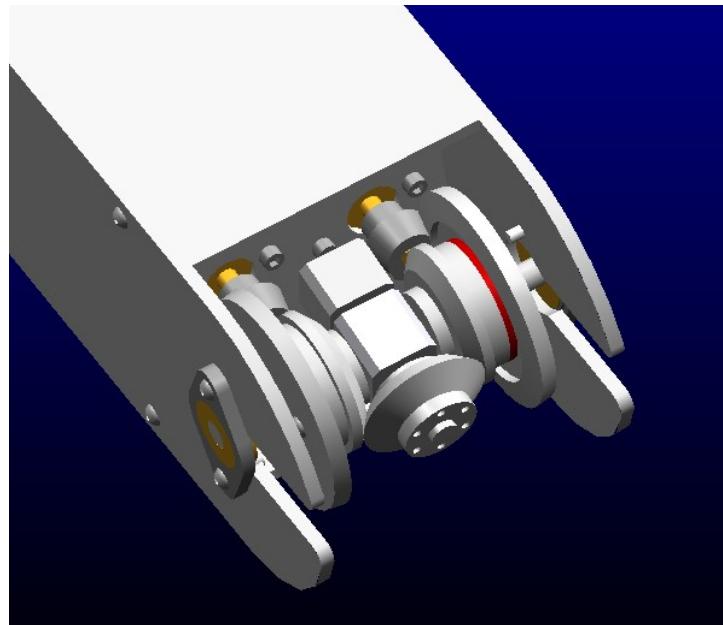
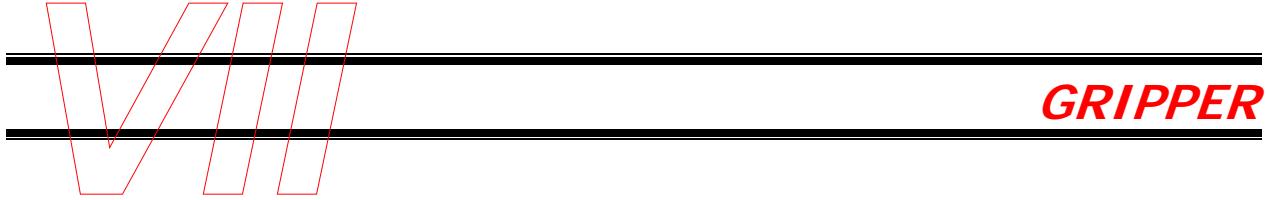


Figure 6.4 - Wrist Differential

Although the differential gear set, purchased from Sterling Instruments, was one of the most expensive components purchased for the arm, the mechanical advantages were deemed to appropriately offset the high cost of the product. Providing two degrees of freedom within a small space was essential to maximizing the movement and functionality of the robotic arm design.



7.1 RESEARCH AND CONCEPTS

The previous Gateway teams invested much time into gripper design and some very interesting ideas were developed. Two designs were mainly discussed: the 1999-2000 design, and Chris Fearon's graduate design. Other previous designs were quickly determined not to meet the goals of this year's team.

Chris Fearon designed a gripper that was very efficient at picking up large objects (1.5 to 3 inches) but had some trouble with small objects. He used three fingers (as opposed to the previous Gateway teams two-finger wrench designs), which allowed for more stability and a greater variety of objects that could be handled. Much of the work went into the analysis of the fingers and the loads that they could handle. Chris did extensive research and testing using ANSYS to pick the best finger design that would limit finger deflection and stress points.

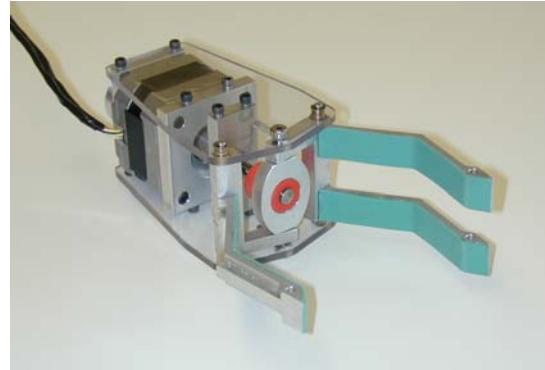


Figure 7.1 – Fearon's final gripper design

Aluminum was chosen for the major components of the fingers and moving pieces of the palm. The motor was also locked into place using aluminum plates. The side cover plates were made from Acrylic simply for aesthetics. These two materials offered high strength to weight ratios and were fairly low in cost. Actuation was handled through the use of a stepper motor/leadscrew system. The NEMA size 17 stepper motor from Applied Motion and a lead screw and power nut assembly from Precision Industrial Components Corp. were the products purchased. The thrust bearing was used to eliminate the thrust force that would be placed on the motor due to heavier objects. The high torque size 17 stepper motor provided 31.4 in-oz of torque at 300 rpm, which is more than enough to overcome the joint friction and operate the gripper. The overall cost of material and machining for Chris' gripper was about \$620 for a

prototype and about \$430 for production of 50 or more assemblies. A solid edge model of Chris Fearon's gripper is shown in Figure 7.2.

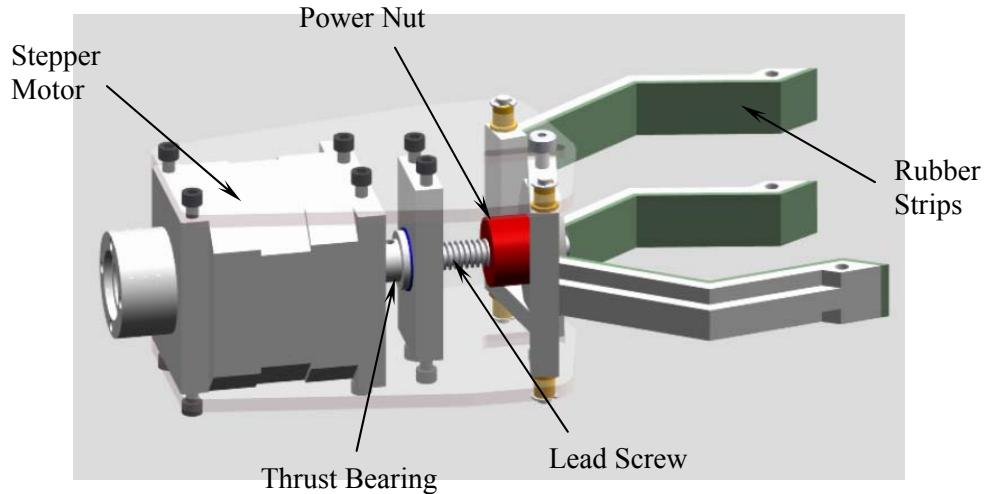


Figure 7.2 – Fearon's Solid Edge Model

The 1999-2000 Gateway team took a different approach to the design. They took Chris Fearon's design to the next level by implementing underactuated fingers. A mechanism is underactuated if it has fewer actuators than degrees of freedom. This type of design allows the fingers to wrap around an object as it closes and to pick up a wide variety of objects (small and large). The group then decided to use a six bar, underactuated, two degree of freedom linkage. This design took much kinematic research and testing. An example of a six bar linkage closing around an object is shown in Figure 7.3.

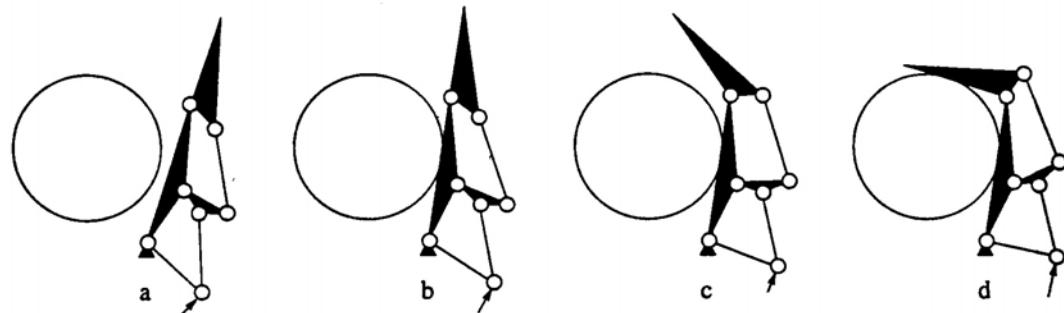


Figure 7.3 - Closing sequence of an underactuated system.

This design could pick up cylindrical objects ranging in size from 1 to 4 inches. Forces were studied and parts were designed to reduce stress concentration and machining costs. This meant rounding edges to create more “dumbbell” shaped parts. Most of the components were constructed of aluminum, but the side plates and finger pieces were made of Lexan. The gripper was again actuated by a stepper motor/leadscrew system. The Ht17-070 stepper motor from Applied Motion Products, and a $\frac{1}{4}$ -inch leadscrew from PIC design were the products purchased. A $\frac{1}{4}$ -inch aluminum plate was moved by the leadscrew and slid in slots cut into the sideplates. This motion is what closed the fingers and actuated the six bar linkage.

This turned out to be a very cost effective design as well. One of the main reasons that Chris Fearon did not invest much research into the use of an underactuated system is that he thought the cost would be too high. After all of the kinematic analysis and design was finished, the actual machining and material cost was only \$547. This was actually a lower cost than Chris Fearon’s prototype gripper. A production cost was not calculated for the 1999-2000 gripper but would have been even lower due to the reduced cost of machining.

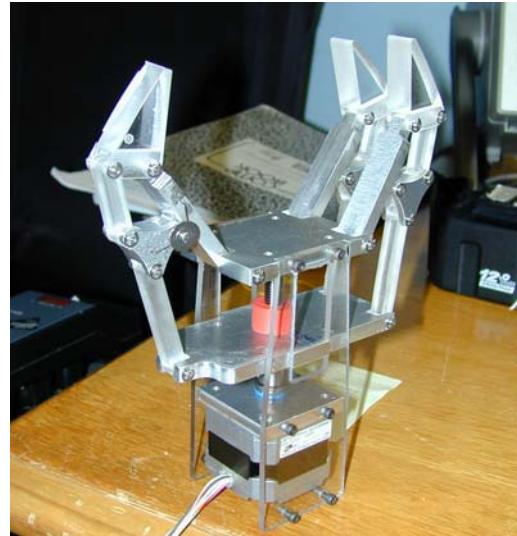


Figure 7.4 - 1999-2000 Final Assembly

7.2 DESIGN AND ACTUATION

This year’s design team used most of the design from the 1999-2000 team but made several modifications to increase durability and ease of control. The first design change was that we eliminated the use of Lexan. We believed that this material was used more for visual purposes than for the mechanical benefits. In examining the old gripper, cracks had formed around the areas of high stress caused by the screws. The Lexan is also much more flexible, which allowed the side plates to bend and twist fairly easily. Aluminum was chosen to replace

these parts. Aluminum made the frame much more stiff and durable without adding very much weight. The cost of aluminum is also quite low, and it is easier to machine than Lexan.

Another design change came with the use of a cordless screwdriver motor. The motor chosen was a 2.4 VDC Johnson Electric and was found in a Black and Decker Model #9072 screwdriver. The screwdriver itself came with a gearbox that was also used in the new design. The planetary gearing used provided an output of 20 in-lbs of torque at 150 rpm. This was very appropriate for our application because it allowed for the gripper to move its full range of motion in about 4.8 seconds. There was



Figure 7.5 – Comparison of old/new motors

also a cost benefit associated with the use of this product over the old stepper motor. The Ht17-070 cost \$50, but the entire cordless screwdriver only cost \$15.

This cost savings was offset by the addition of new components, but the main reason for choosing this motor is for consistency and ease of control. One issue that we wanted to solve this year was that we wanted to use a consistent type of motor. The stepper motors were very difficult to program using the OOPic controller. A stepper motor offers the ability to know the exact position of the motor at all times. However, we do not need to know the exact position of the motor for this application. The opening and closing of the gripper can be controlled visually with sufficient accuracy. The screwdriver motor has the advantage of not being back drivable. This eliminates the need for any braking and allows the gripper to maintain a tight grasp on an object without drawing any current.

Several components were re-designed and several more were modified to complete our final product. One drawback of the new design is that it is about 2.7 inches longer and slightly heavier than the previous year's gripper. This is a tradeoff that we were willing to accept to achieve our previously discussed motor control goals. The length of the motor and gearbox was what caused the major design changes. This required lengthening the side plates to house the new equipment. Since these plates were now longer, they needed to be even more rigid (another reason for choosing aluminum over Lexan). Also, the old plate that housed the motor had to be modified and moved in order to support the new motor/gearbox assembly. This support plate fits

around the Johnson Electric motor and rests against the bottom of the plastic housing of the gearbox. This plate was then fixed into place using epoxy. Fastening using epoxy was not the desired way to attach the motor to the plate, but was used due to time constraints at the end of the project. The original idea was to weld the support plate to the motor housing (A gas tungsten arc-weld, or “Tig” weld, would have been used because of the thin housing of the motor and the joining of aluminum parts).

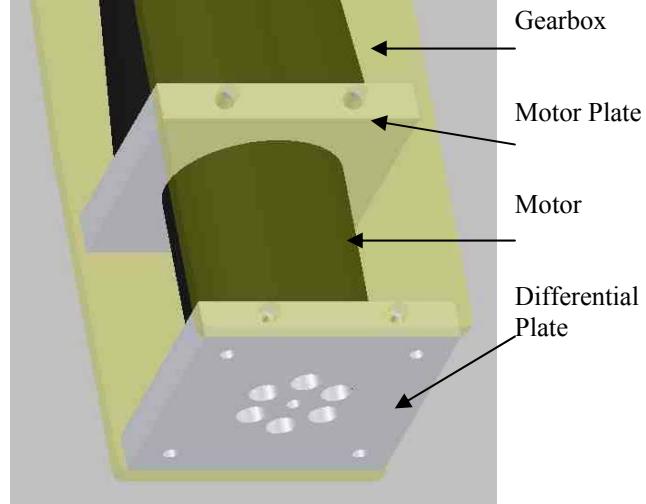


Figure 7.6 – Motor and Differential Plate

The motor/gearbox assembly was not modified as it came from the screwdriver. The only modification was that the fixture on the end of the gearbox output shaft was reduced in length by $\frac{1}{2}$ of an inch. Originally, a screwdriver was dissected to see what parts could be eliminated and how the output of the gearbox could be fastened to the leadscrew. These screwdrivers were difficult to disassemble without damaging the components. Therefore the decision was made to make use of the hexagonal shaped slot that was already part of the screwdriver. A special coupling was machined with a hexagonal insert on one side and an identical match to the leadscrew on the other end. This allowed for the use of a coupler to join the two pieces.

Because the 1999-2000 gripper design was used as our baseline, the components discussed above were the only parts that were fabricated from scratch. The remaining parts of the gripper were re-assembled and re-used, with the exception of the finger pieces. These pieces were also re-machined from aluminum instead of Lexan for consistency of appearance. The mounting and dynamics of the gripper are identical to those of last year’s design. The gripper is mounted to the wrist differential by fastening the bottom plate by using six screws (the differential plate can be seen above in Figure 7.6). This plate also serves as protection for the motor itself. Because of interference between the gripper and the forearm housing, a spacer had to be added to create a slight separation.

The gripper is again actuated through the use of a leadscrew that moves a plate that slides in slots milled into the side plates. The motion of this plate is what begins the movement of the six-bar underactuated linkage. The upward motion of the plate forces the fingers of the gripper to close until they make contact with an object. After contact has been made, the joints in the fingers will bend. The bending of the joints is what allows for the fingers to “wrap around” an object to create a firm hold. This idea is shown in Figure 7.3 but can also be seen in the closing sequence of the assembled gripper that is shown in Figure 7.7.

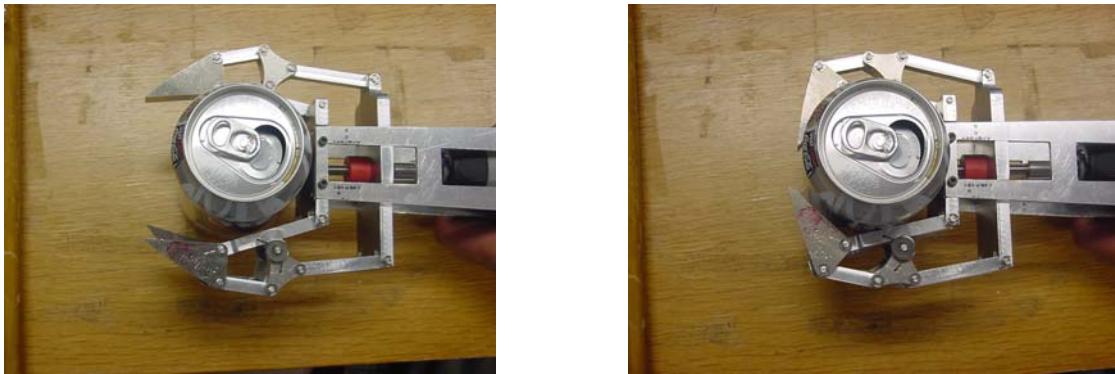


Figure 7.7 – Physical Closing Sequence of the Gripper

The final prototype cost of the gripper was determined to be \$524.26 and \$414.88 for a production volume of 50+. Notice that the cost of the gripper is very similar to that of last year’s design (\$547.05 for 99-00 design prototype). However, the lack of cost savings is made up by the ease of control that was created by using the screwdriver motor. The difference in price for a production volume of 50 or more assemblies is mostly due to the reduced cost of machining larger lots of parts. This was estimated in the calculations by reducing the machining time by 25% (from 17.5 hours to 13.125 hours). The cost of the gripper components, material, and machining is summarized in Appendix A (Bill of Materials).

A disadvantage of this year’s gripper design is the increase in length (from 4.60-inch side plate length to 7.25-inch side plate length). However, the arm design allowed for a maximum gripper length of 12 inches, which we are still well below. The final Solid Edge gripper assembly is shown in Figure 7.8.

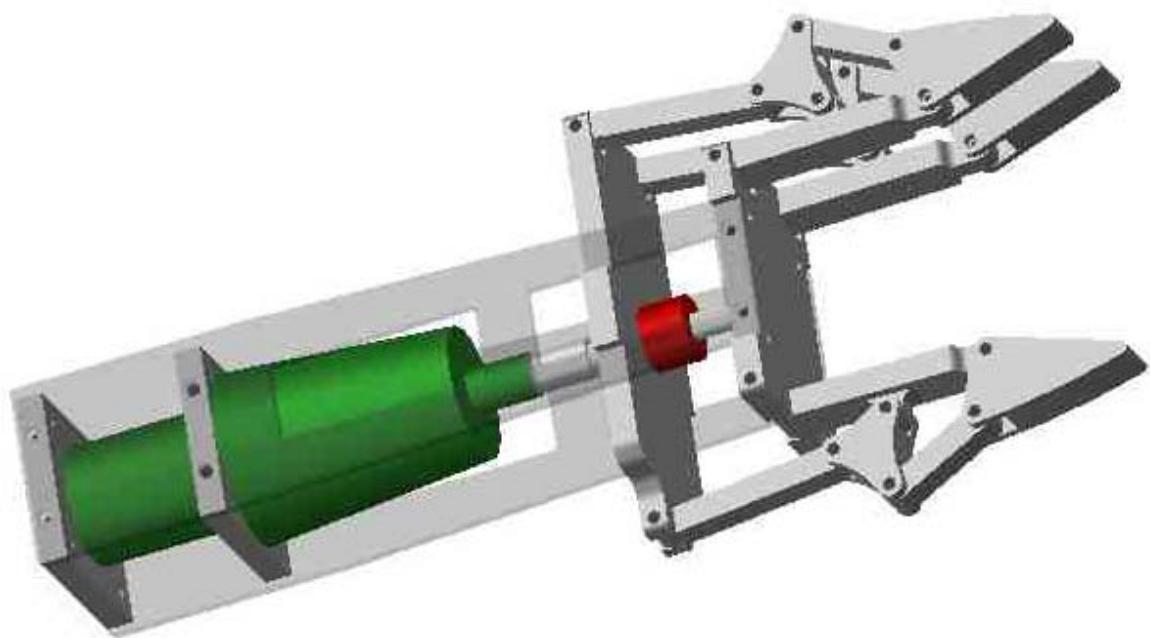
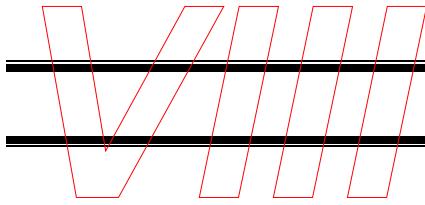


Figure 7.8 – Final Solid Edge Gripper Assembly



MOTOR TESTING

8.1 MOTOR RESEARCH AND SELECTION PROCESS

Through the initial literature search and a trip to Motoman in Dayton, Ohio, several motor options were defined. The overriding decision was whether to proceed with AC or DC motors. Previous design teams have utilized DC motors, since the wheelchair already had this power source available. AC motors, however, presented some enticing options specific to the project that merited further investigation. One such advantage is the wide spread use of AC motors in industry. This is a two-fold benefit; the cost of these motors should be lower, for a given set of characteristics, over a similar DC motor due to their widespread use, second any control specific questions might more easily be answered by those in industry since they are more likely to have faced similar questions in their own designs. Another advantage AC motors have over DC motors relates to the power consumption of the motor at its different states. As pointed out by Michael Ondrasek, an engineer from Motoman, AC motors require the least amount of power in a holding position and the most power while running at full speed, in the case of DC motors the most power is required at stall and the least power is required while running at full speed. The AC motor characteristic seems to better suit the needs of the Gateway design, since the arm will spend a good deal of time in a rest or stationary holding position.

The AC motors are not without their drawbacks however. Two main concerns are the need for an inverter and the speed-torque characteristics of AC motors. First, the need for an AC inverter, to convert the available 24 VDC to 120 VAC was investigated. Since DC drill motors were being considered, as a cost saving measure, the same thinking applied to AC motors. In the current arm design there are five main motors, to get an idea of the size of inverter required, Statpower, a company that specializes in power conversion, maintains a list of typical appliances that can utilize their power conversion equipment. This list is shown below in Table 8.1.

Table 8.1 –Power Consumption of Typical Appliances

Typical Appliance	Est. Power Requirements
Cell Phone Charger	10-20 Watts
Camcorder	15-30 Watts
Video Games	20-30 Watts
Fax Machine	30-40 Watts
VCR	40-55 Watts
Soldering Iron	45-60 Watts
Laptop	70 Watts
19" TV	70-110 Watts
100 W Work Light	100 Watts
3/8" Drill	500 Watts
Blender	650 Watts
Circular Saw	1,800 Watts

According to Statpower and several other inverter manufacturers, small motors like those found in power tools require between 400 and 500 Watts of power. This being said, the Gateway arm fitted with five AC drill would require between 2000 and 2500 Watts of power from the AC inverter. Because of the price of this size inverter, it was determined that the cost outweighed the benefits. MajorPower, a large supplier of power inverters, carries several models in the 2500W range, that retail for between \$1,800 and \$2,000. Other drawbacks to the power inverter option are the dimensions and weight of the inverter. The 2500W inverter from MajorPower weighs 32 pounds and has overall dimensions of 20" x 15" x 5.5", which would make it difficult to position the inverter in a suitable place on the wheelchair for accessibility to the occupant or for the protection of the device. The inverter also adds unnecessary complexity to the design. For example, operating the controls for the inverter would be difficult for the disabled user, and any malfunctions or blown fuses would disable the arm. Although AC drill motors are less expensive for similar capacities, the large cost of the inverter all but negates this advantage. The second disadvantage to AC motors is the need to run the motor at high speeds to obtain the rated torque for a given motor. AC motors produce most of their torque at higher speeds, and this torque drops off rather quickly as the motor speed is reduced. The Gateway design does not require high speeds in any of the main motors, so additional gearing would be required to obtain the necessary torque at lower speeds. This gear reduction adds weight and additional cost to the design. Therefore these drawbacks outweigh the gains AC motors have over DC motors.

Once DC motors were determined to be the choice for the Gateway arm, the next decision relied upon, which type of DC motor to use. In previous Gateway designs, several

different types of DC motors were used because the motor's specific advantage provided the best result for a specific arm function. This allowed the arm to be optimized with these different motors, but made controls a more tedious job trying to balance the various inputs and outputs required by the assortment of motors. The decision was made to settle upon a single type of DC motor, simplifying the controls, and the different interfaces needed by each type of motor. The main advantage to any of the different types of DC motors is the ability to produce many different speed-torque relationships that can be easily tailored to the needs of the project. Most DC motors when properly configured can also produce as much as three to five times their rated torque for short bursts. Wound DC motors, permanent magnet DC motors, and brushless DC motors were three types considered for the Gateway arm. Stepper motors were not considered, since the power requirements for the arm were above those provided by reasonably priced stepper motors. Brushless DC motors were considered briefly since they react more like AC motors than DC motors. They also exhibit more durability than conventional wound DC motors since they contain no commutator or brushes, which wear over time. This advantage is also a disadvantage since the added circuitry increases the overall cost of the motors. This leaves permanent magnet motors and wound DC motors. Permanent magnet DC motors provide many of the same characteristics of wound DC motors, but variability in the magnetic material that goes into construction can lead to inconsistencies from motor to motor. The PM motors are also susceptible to shock, vibration, and temperature variations that are not concerns for wound DC motors. The final DC motor option considered, are wound DC motors. These motors come in several configurations that lead to varying control options and motor characteristics. These configurations include: series wound, shunt wound, and compound wound. The series wound motor is useful for low speed-high torque applications, but has high starting torque and poor speed regulation. The shunt wound motor is available in both long and short varieties and provides good speed regulation and a flat torque-speed curve. The compound motor is a combination of a series wound motor and a shunt wound motor. It provides a compromise by offering better starting torque than the shunt motor, but less accurate speed regulation. The DC motor obtained from a cordless drill is most likely a series wound DC motor.

8.2 MOTOR TESTING

The previous arm designs utilized expensive specialized actuators and gearboxes to provide movement. A main goal for this year's design was to reduce cost. Consumer products afford the cost savings of mass production. After researching the available cordless products, the cordless drill had the best combination of a motor torque rating and gearbox. The drills researched ranged in price from \$100 to \$200+ and the advertised torque ranged from 210 to 500 in-lb. In the interest of time saving a baseline inexpensive drill would be tested with future purchases based on how well the test drill faired.

The test drill purchased was a Black & Decker 18.0 Volt Firestorm, Model HP932K-2. The drill was disassembled and the key parts are shown in Figure 8.1. The main components are the motor, speed control, gearbox, and clutch pack. The gearbox consists of three sets of planetary gears. The two sets closest to the motor that are under the lowest torque have plastic idler gears. The speed rating on the drill is 0-400 rpm for low range and 0-1400 rpm on high. For our application low range would be tested. The low range has a gear ratio of 21.4:1. The clutch packs of the drill enable a maximum torque limit. As a safety factor the packs could be set to reduce the maximum force provided to the arm. For all testing, the packs were set to the drill mode, which delivers the maximum torque available. The motor was rewired at its terminals to provide current and voltage readings for testing.

A Magtrol HD-710 model dynamometer was used for testing. This dynamometer uses a strain gage to calculate torque input to a brake unit. This strain gage has a voltage output that is converted back into a torque output. An encoder produces a pulse frequency and an oscilloscope was used to convert to rpm. A stand had to be designed and built so the drill could be effectively coupled to the brake unit. The stand was designed to be adjustable in the horizontal and vertical axes to accommodate different drills for future testing.



Figure 8.1 - Firestorm 18V drill motor and accessories

See Figure 8.2. Since the drill had a 3/8-inch chuck a shaft was designed to transmit torque to the brake. Three milled flat lands were placed on the chuck end of the shaft to eliminate the possibility of slippage of the chuck. A keyway was placed on the brake end to drive the dynamometer. See the shaft in Figure 8.3. The shaft completed the mechanical changes to the stand. See the final setup in Figure 8.4.

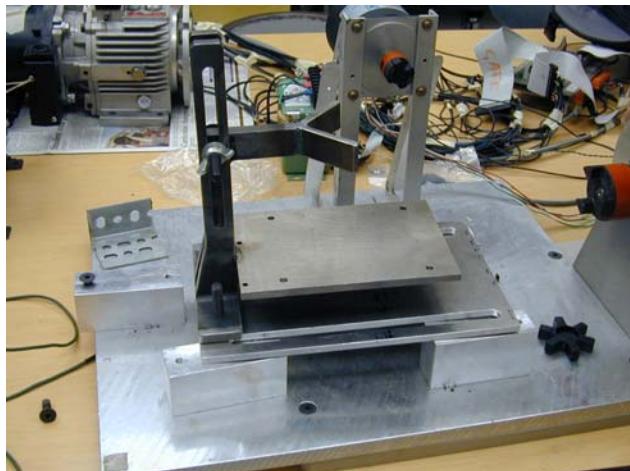


Figure 8.2 – Motor Test Stand



Figure 8.3 - Shaft

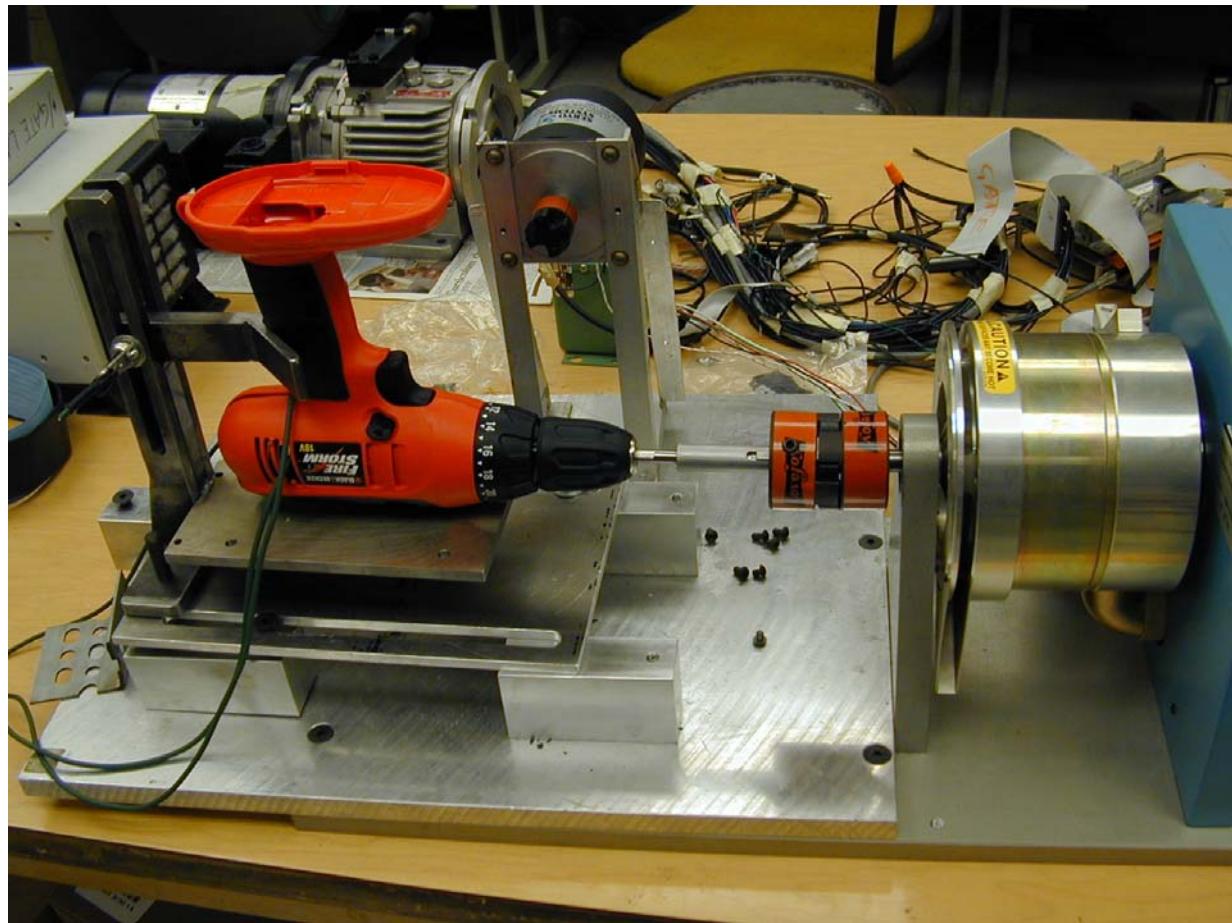


Figure 8.4 - Test Setup Magtrol HD-710

The Magtrol required both 22 volt and 5 volt power supplies to operate the data outputs. An automotive 12-volt battery was wired in series with an adjustable voltage supply to deliver the 22 volts. This was done because the voltage supply had a maximum voltage of 17 volts. A separate 5-volt supply was used for the 5 V circuit. The connector shown in Figure 8.5 was wired to provide the input power to the data acquisition of the Magtrol. The testing procedure, which was followed to carry out the testing, can be found in Appendix E.

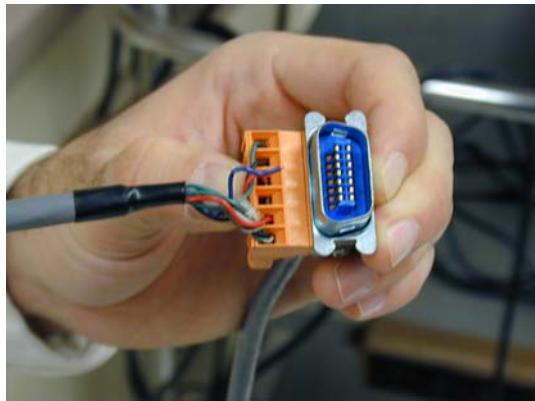


Figure 8.5 - Power Input Wiring to Magtrol HD-710

Testing of the setup proved very brief. Unfortunately, there was a short between the 22 V and the 5 V circuits. Two loud pops were heard and electrical smoke emanated from the stand. We think the short occurred in the orange end of the connector. The Magtrol case was opened and a 15 V voltage regulator was destroyed along with a capacitor. See Figure 8.6 for a photo of the board components. These parts were inexpensive, \$1.45 for the voltage regulator, and hopefully they will fix the board. Magtrol was contacted and a replacement board costs \$175. The team installed a new control board, and the dynamometer was recalibrated. At this time it was determined that the tachometer encoder was also damaged, preventing accurate speed dynamometer speed measurements. This component was ordered and replaced at a cost of \$55 dollars. The only data obtained in the brief test was that the motor drew a maximum current of 35 Amps at the 18.0 V battery voltage. At this high torque load testing the 1 amp-hr drill battery was drained in less than three minutes. After all the part replacements, and recalibration, the dynamometer did not produce the required data for motor torque speed curves, since the dynamometer only produced usable data up to 3.4 N-m (30.19 in-lb).

Figure 8.7 shows the torque speed curves for the motor alone provided by the motor manufacturer, Johnson Electric. Because the maximum torque provided by the motor and 57.6:1 drill gearbox combination was approximately 250 in-lb, this motor could be used in the shoulder joint with gear reduction to increase torque and decrease rotational speed. Gear ratio calculations and gearbox efficiency calculations are shown in Appendix E. A further 80:1 reduction would be required to reduce speed from 400 to 5 rpm as required by the arm design, the cost of this gear reduction would negate any savings gained by the use of motors obtained from mass produced consumer goods.

The cost-prohibitive nature of the drill motor adaptation, led to a search for alternative motor and gear drive combinations. Upon further investigation, a supply of surplus gear motors was located. These motors operated on 24 VDC providing 325 in-lb of torque at 35 rpm. These motors utilize a worm drive mated to the electric motor to provide this reduction.

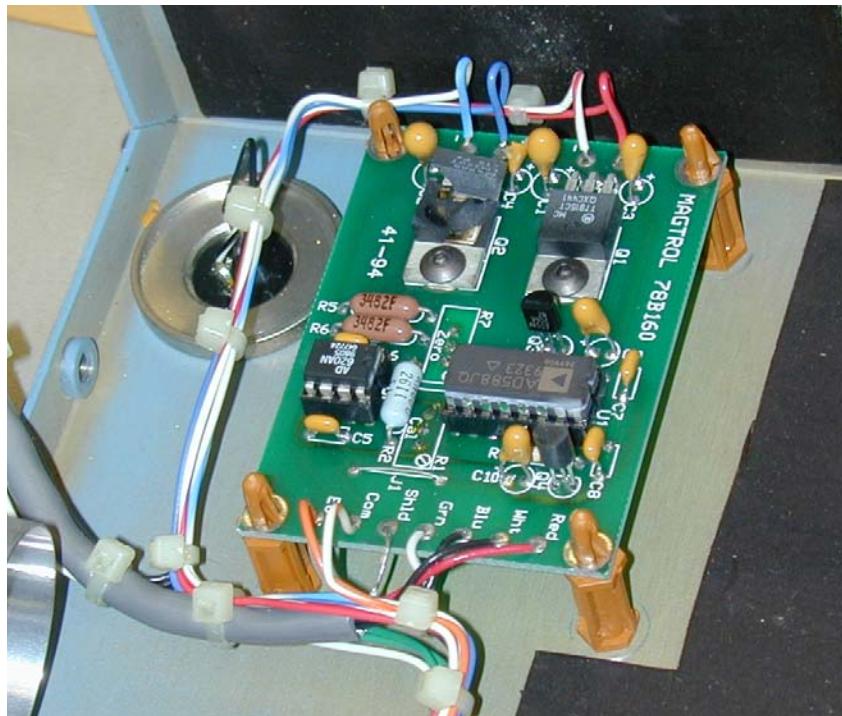


Figure 8.6 – Damaged Dynamometer Control Board

JOHNSON ELECTRIC ENGINEERING LTD.

6-22, Dai Shan St., Tai Po Industrial Estate, N.T., H.K. Fax: 852-2683 6108

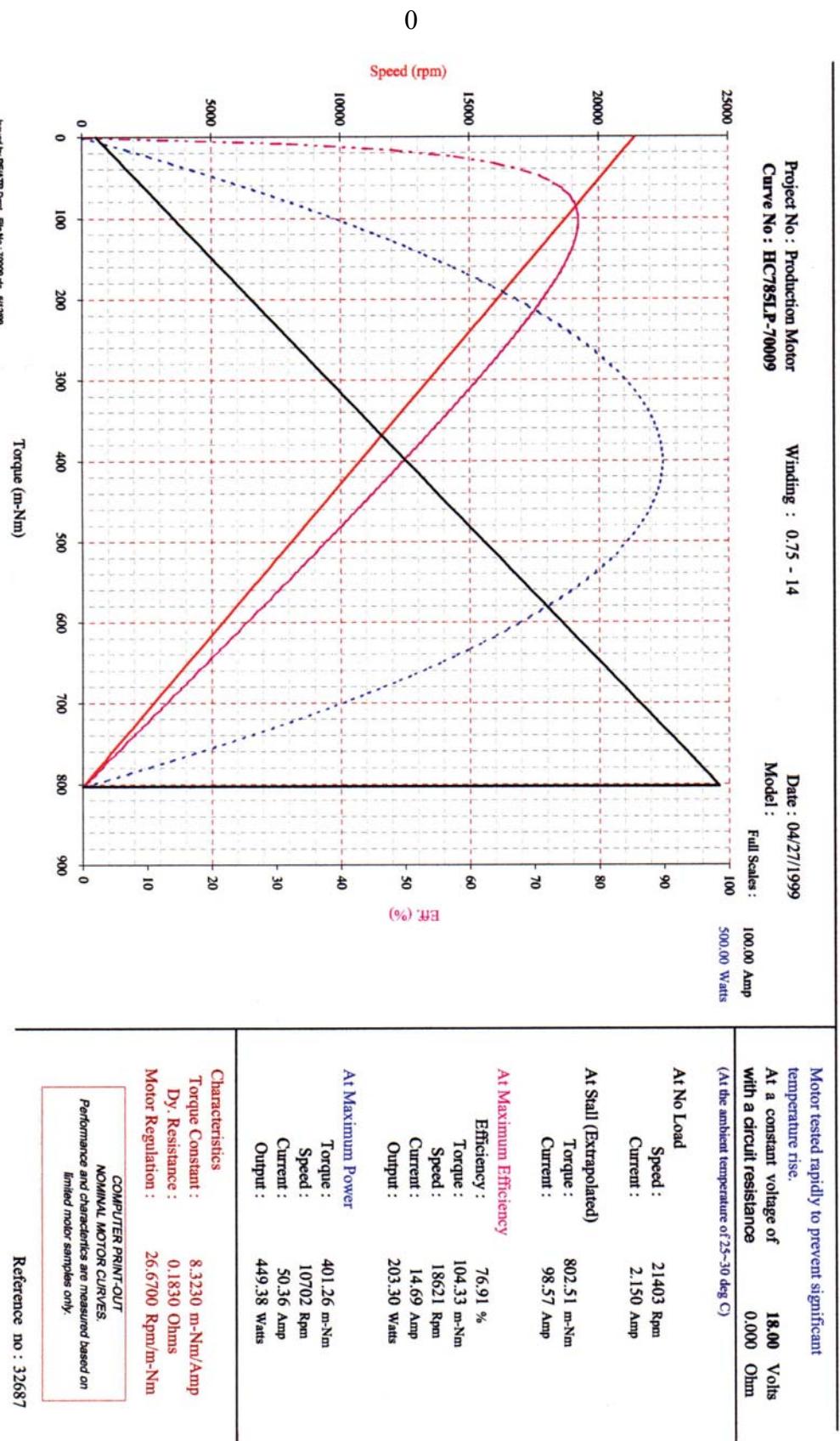
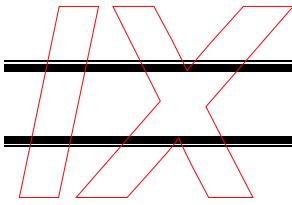


Figure 8.7 - Drill Motor Torque Speed Curve



CONTROLS HARDWARE

9.1 MICROCONTROLLER

To provide adequate control of the six different motors located in the arm, the selected motor controller is required to meet several requirements. These requirements include cost, ease of programming, number of I/O lines, Analog-to-Digital (A2D) converter, and processing speed.

The most important of these considerations is cost. Since the project has a limited budget and power constraints, a commercially available motor control system would be out of the question. These products would utilize a disproportionate amount of the available budget. The goal of the project is to keep the costs low, making the device available to a greater percentage of the populous.

While cost was an important consideration, ease of programming was also a priority. The team members were eager to learn new programming languages and techniques, but the limited time frame required the use of familiar languages. Most controllers on the market utilize assembly language, which was unfamiliar to all of the team members. This limitation narrowed the list of viable options to two microcontrollers, the BASIC Stamp and the OOPic.

When comparing these two options, some obvious advantages developed. The first major advantage of the OOPic over the Stamp is the multitasking capability of the OOPic. This advantage is important for simultaneous kinematic calculation, while changing multiple motor speeds. The OOPic also allows for more operations per second thru the use of virtual circuits, and twice the I/O line capacity of the Basic Stamp. The OOPic has an internal Analog-to-Digital converter, providing potentiometer input for closed loop feedback control. This A2D converter operates at 8-bits providing 256 divisions over the range of measurement. Additionally, the OOPic provides networking capability between multiple controllers. Furthermore, the OOPic was



Figure 9.1 – OOPic microcontroller

among the microcontrollers proposed as a future suggestion by previous Gateway teams. Finally, the OOPic compiler supports Basic, C, and Java languages, while the Stamp has a proprietary PBASIC command set. C and Basic programming were among the skill sets possessed by several group members. Figure 9.1 shows the OOPic microcontroller.

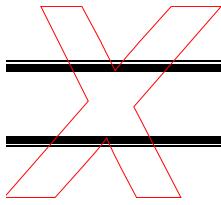
9.2 MOTOR CONTROLLER

In past years, Gateway groups had designed and built special motor controllers to fit their needs. This specialization was necessary due to the large variety of motors used in previous designs. For 2001, one of the goals was to use one type of electric motor for the arm tasks. Previous years designs utilized brushless DC motors, stepper motors, and DC servomotors. Each of these motors required different programming and hardware schemes. This assortment of motors added complexity to the design without much benefit to the customer. In this year's design, the team was able to locate a source of surplus motor controllers with favorable characteristics to the surplus gear motors selected for this project. These model MC6 motor controllers provide 30 amps continuous control by a Pulse Width Modulation signal supplied by the OOPic microcontroller. The motor controller has a built in ramp function for a smooth startup in both forward and reverse directions. The inputs required from the OOPic are +5V enable signal, to engage the motor control board, two direction signals, and a PWM signal for speed control. As an added benefit, these boards are available in both 12 VDC and 24 VDC configurations.

Problems surfaced when using these boards to control the screwdriver motors, located in the gripper and elbow, and the window motor used in the shoulder rotate. Electro Magnetic Interference (EMI) was caused by the "noisier" motors. This EMI feedback caused the OOPic to randomly turn on and off I/O lines. We made an attempt to filter this noise using $0.1\text{-}\mu\text{F}$ capacitors mounted between the motor power leads and each lead to the motor casing. This solution fixed the noise originating from the window motor. To reduce the noise to a level that would allow the OOPic to control the screwdriver motors a separate power source was required. The battery used was a 6 V lantern battery with a common ground to the wheelchair. This eliminated power supply line noise. To eliminate this extra power source, reduction of noise in the power lines would be required. An inexpensive fix would be to use ferrite cores around the power lines leading to the OOPic.

9.3 ANGLE MEASUREMENT FOR CLOSED LOOP FEEDBACK

Two types of measurement devices were investigated for determining the joint angles. Both encoders and potentiometers were considered. Absolute encoders were considered more favorably over incremental encoders, since they did not require an initial home position for angle measurement. The cost of the absolute encoders, at around \$1000 for each of the encoder assemblies, made them an unacceptable option. Incremental encoders are a much cheaper option, about \$100 per encoder, but require the arm to return to a home position prior to any angle measurement. This characteristic, as well as, the increased processing requirement made incremental encoders an unacceptable option. The next type of measurement device explored was the use of potentiometers. Initial analysis of the potentiometer precision needed for the feedback control required more processing than the 8-bit A2D available from the OOPic. Upon further investigation, all angle measurements were limited to less than 360° , thus spreading the 256 divisions over a smaller angle range.



CONTROLS

10.1 KINEMATICS AND CONTROL STRATEGY

The team studied the kinematics of the arm to understand its motion. The robot arm moves in 3-D space, so a natural instinct was to attempt to analyze its movement in three dimensions. However, this method of analysis would have been very complicated and unnecessary. The analysis was simplified to two dimensions, because only the movement in the plane of the arm needed to be considered. The arm's angle of rotation about its base was not important to the kinematics. In other words, the orientation about the z-axis (vertical axis) was ignored. Further simplification of the kinematics analysis procedure was still desirable. The control strategy was to control the movement of the gripper in one direction at a time, either horizontal or vertical. Therefore the kinematics needed to address the speed of the gripper moving linearly in one direction at a time. In other words, the arm wouldn't rotate about its base and extend the gripper at the same time. Considering this from a kinematics standpoint, the kinematics of the arm was simplified to a three-link open chain. The arm is depicted as a simple linkage in Figure C.1 in the Kinematics section of the Appendix. The analysis is shown in detail in that section.

The team wanted to make the arm as simple to operate as possible for the user. Optimally we would have implemented speed control at the shoulder, elbow and wrist joints. Incorporating the ability to adjust motor speeds using the results of the kinematics analysis would have allowed the user to move the gripper in one direction, either horizontal or vertical, at a constant speed. This would have incorporated equations (7), (11) and (12) from the Kinematics section of the Appendix, to regulate the motor speeds. Using this control scheme would have required some way to measure the joint angles, such as encoders or potentiometers. This control strategy was not implemented due to time limitations.

Another strategy for controlling the arm lies at the other extreme for ease of operation for the user. This strategy is to control each degree of freedom individually. No speed control would be necessary, and therefore there would be no need to measure the joint angles. This

control strategy was developed initially, and maintained as a backup. However, a more user-friendly strategy was implemented in the final arm.

The control strategy used in the final design of the arm is a combination of the single motor control without speed control and the strategy of controlling three degrees of freedom simultaneously using speed control. The team designed the controls similar to the single motor control structure. However, the ability to control two degrees of freedom was added. Using relationship (7) in the Kinematics section of the Appendix, the control code was structured so that the wrist bend would always function in unison with either the shoulder bend or the elbow bend. This is a great benefit over simply controlling each degree of freedom individually, because it forces the grippers orientation with respect to the ground to remain fixed while the elbow or shoulder bend is actuated. This has many benefits to the user. For example the operator could use the arm to pick up a glass of water and the controls would make sure that no water was spilled by keeping the gripper level with the ground.

There are several disadvantages to the control strategy we used, however. For one the gripper cannot be made to move only in a horizontal or vertical direction, but will always move in a combination both horizontally and vertically. Also, the gripper's linear speed is not fixed in this control strategy, and does not remain constant as the arm moves.

10.2 OOPIC AND CODE DEVELOPMENT

The OOP in OOPic stands for object-oriented programming. In this scheme, objects are created and various properties of these objects are manipulated in order to achieve the desired output. In the OOPic, all of the embedded controller's hardware circuits are grouped into objects. Now, instead of each of the controller's circuits having to be called individually, circuits that will act together in the code are given one object name. This, once the programmer is familiar with the objects, can greatly simplify how the code is written. This section recounts the process of learning object-orient programming and how the code evolved as the team's knowledge increased. It also touches on why control of the arm using the kinematic equations was not used and what multi-motor control is implemented using a simplified kinematic approach.

The first task was to become familiar with the basics of OOPic programming and operation. First off, it was decided to program in C because that is the language that the team

had the most experience with. Then, as a test, a sample code that was provided by Savage Innovations (the OOPic's manufacturer) was downloaded into the OOPic. This code was to simply have a LED flash on and off once a second.

The next task was to modify the sample code by integrating a Virtual Circuit. This again was provided in the OOPic's manual. It became evident early that Virtual Circuits would be the most important part of the control code, so it became vital to become familiar with their operation early in the programming phase. A Virtual Circuit links a property of one object to the property of another. This allows the code to constantly monitor a specific value and have this value continually updated in the code. This is important for monitoring things such as joystick input and system feedback. Virtual Circuits also allow the code to enter events, or subroutines, which are vital to the system's operation.

After becoming familiar with the operation of the OOPic, Virtual Circuits, and event driven programming the team began to develop code for single motor control. This code involved reading a joystick input, determining whether the input was for motor forward or backward, and then entering an event to carry out the operation. At first it was built into the code to send a quick ramp up or down of the PWM signal being sent to the motor control board for starting and stopping the motor respectively. It was later found that the motor control boards would automatically ramp the motor speed up as long as the motor enable switch was reset every time the motor was started. This was integrated into the single motor control code along with a PWM step down for the motor slow down event.

The final phase of the programming considered trying to get all of the motors to act together through the kinematic equations and feedback using potentiometers. The first test codes written were to test the potentiometers connected to the OOPic. This was done by turning on various input/output lines depending on potentiometer position. The potentiometers were then used to vary the PMW output to the motors and thus affect the motor speed. Both of these codes worked very well. Unfortunately, the time that it would take to implement a system with the potentiometers and kinematic equations was too long, and the team ran out of time to make an attempt at this. Next year's Gateway team should have an easy time starting where this year's team left off and be able to construct a completed speed-control system with potentiometer feedback fairly easily.

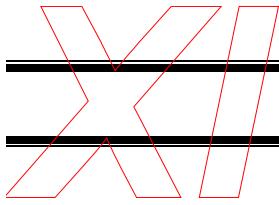
In light of these problems it was decided that multi-motor control to keep the arm operating in one plane at a time was not feasible to accomplish by the end of this academic year. It was decided, though, that a simplified multi-motor control scheme could be implemented with little problem. This scheme would not require the use of a feedback system. Basically, the simplified control scheme ensures that the gripper will stay level with the ground so that the orientation of the item in the gripper would not change after it has been grasped. This is particularly useful when the user does not want objects, such as a glass of water, to be tipped when he or she is manipulating it.

One final feature that was implemented was a one second delay of the gripper actuation. This feature is intended to protect against an inadvertent movement of the joystick that would normally cause gripper movement. The benefit being that an accidental movement of the joystick will not allow the object in grasp to be released.

In order to implement the control of 6 motors in a user-friendly fashion, 3 joystick modes were used. There are a total of 12 operations that are controlled by one four-way joystick and three switches. A list of the mode operations is shown in Table 10.1 below. These operations were assigned in an intuitive fashion to simplify use of the arm. Note that the shoulder bend and elbow bend commands incorporate the wrist leveling algorithm.

Table 10.1 – Control Modes

MODE	LEFT/RIGHT	FORWARD/BACK
1	Shoulder Twist	Shoulder Bend
2	Wrist Bend	Elbow Bend
3	Wrist Twist	Gripper Open/Close



FUTURE CONSIDERATIONS

11.1 GENERAL

There are several items that need improvement and they should become part of a new team's objectives:

1. Improve the center of gravity of the arm by using lighter components and moving heavy objects, such as the motors, further down in the arm. The use of belts has been examined in the past and was found to be rather expensive, but this would greatly reduce the center of gravity of the arm.
2. Make the arm lighter by selecting lighter materials and components or further redesigning the arm.
3. Investigate other ways to draw power off of the two twelve volt batteries. This year, both batteries were wired in series to get the 24 VDC, but all of the current was drawn off of the grounded battery. This caused this battery to drain at a high rate.

11.2 MOTORS

This year's team tried to be consistent with motor selection to simplify controls and design. This idea seemed to work very well and should be improved upon in the future. The goal should be to use as many of the same motors as possible. Also, DC motors should be the focus of study for the future teams because they tend to be very compatible with the controls and the wheelchair.

11.3 GRIPPER

This year's gripper design worked fairly well, but there are several things that could be changed for improved performance. The first problem is that the gripper is extremely long. This is not necessarily a problem in operation, but it looks awkward. Another thing that the gripper has trouble with is small objects. Fixing this problem would require a complete redesign of the

fingers and palm. Another suggestion is to somehow attach a hooking device to open things such as drawers and cupboards.

11.4 CONTROLLER

For the next academic year, the Gateway team may want to look into controllers other than the OOPic. Although the OOPic is very convenient to use in some respects, it does have some shortfalls. First, there are other chips available now that are much faster than the chip on the OOPic. Most of the controllers with these chips would need to be programmed in the assembly programming language, which is not as desirable. Also, the OOPic should be able to handle all of the necessary calculations, but there are some problems in getting the OOPic to do all of the math properly. The control system durability should also be improved by eliminating large pulse-width-modulation amplitudes on lower rated motors (i.e. not using 12 volt motor control boards with 2.4 volt motors). Another suggestion is to implement a control code that is able to run the arm only when the wheelchair is turned off.

APPENDIX A

A.1 - SHOULDER, LOWER ARM, AND FOREARM BILL OF MATERIALS

Table A.1 – Shoulder, Lower Arm, and Forearm Raw Materials Costs

Description	Part Number	Vendor	Unit Cost	Qty.	Prototype Cost
3" x 3" x 7', 0.125"-Wall Thickness 6063 Aluminum Tubing	88875K46	McMaster-Carr	\$53.08	1	\$53.08
1/4"-Diameter, 399-mm Black Neoprene O-Ring Round Belt	8060K35	McMaster-Carr	\$4.98	1	\$4.98
12" x 6" x 1/4" Green Oil-Impregnated Cast Nylon Sheet	84845K61*	McMaster-Carr	\$11.01	1	\$11.01
12" x 6" x 3/4" Green Oil-Impregnated Cast Nylon Sheet	84845K22*	McMaster-Carr	\$23.24	1	\$23.24
12" x 12" x 0.125" 6061-T6 Aluminum Sheet	89015K28*	McMaster-Carr	\$16.17	1	\$16.17
8" x 4" x 0.25" 6061-T6511 Aluminum Plate	89155K22*	McMaster-Carr	\$6.49	1	\$6.49
12" x 6" x 0.5" 6061-T6511 Aluminum Plate	89155K44*	McMaster-Carr	\$45.37	1	\$45.37
8" x 4" x 1" 6061-T6511 Aluminum Plate	89155K72*	McMaster-Carr	\$19.38	1	\$19.38
3/4"-OD x 6' 6061-T6511 Aluminum Rod	8974K35	McMaster-Carr	\$16.02	1	\$16.02
2" x 1.5" x 1' 6061-T6511 Aluminum Rectangular Bar	8975K253	McMaster-Carr	\$22.03	1	\$22.03
Subtotal					\$217.77

* Part number is for ordering twice the amount of material actually used in constructing the robotic arm.

Table A.2 – Shoulder, Lower Arm, and Forearm Component Costs

Description	Part Number	Vendor	Unit Cost	Qty.	Prototype Cost
0.625" OD, 0.25" Bore Oil-Lubricated Ball Bearing	S9912Y-E2562FS2	SDP/SI	\$10.33	2	\$20.66
Wrist Motor	GM8724S027	Pittman	\$150.22	2	\$300.44
Wrist Differential	SDP/SI: S9570A-TS3	SDP/SI	\$304.93	1	\$304.93
2" OD, 0.75" Bore Gear	GSS486Y-G	Bearing Distributors, Inc. (Boston Gear Distributor)	\$23.30	2	\$46.60
Wrist Pinion	GSS486Y-P	Bearing Distributors, Inc. (Boston Gear Distributor)	\$19.27	2	\$38.54
1.125" OD, 0.5" Bore Flanged Ball Bearing	E7-S3F	PIC Design	\$25.46	4	\$101.84
3.6 V, 180 RPM Cordless Screwdriver	9074	Black & Decker		1	
20-Pitch, 20-tooth, 1" Pitch Diameter, 0.5" Bore, Steel	Catalog: YA20-1/2 Item: 46133 (Boston Gear Catalog)	Bearing Distributors, Inc. (Boston Gear Distributor)	\$20.00	1	\$20.00
20-Pitch, 60-tooth, 3" Pitch Diameter, 0.5" Bore, Steel	Catalog: YA60A Item: 10550 (Boston Gear Catalog)	Bearing Distributors, Inc. (Boston Gear Distributor)	\$25.00	1	\$25.00
Screws, Nuts, Bolts, Washers			\$30.00	1	\$30.00
Subtotal					\$888.01

Table A.3 – Shoulder, Lower Arm, and Forearm Machining Costs

Cost / Hr.	Hrs.	Prototype Cost
\$25	100	\$2,500.00

A.2 - GRIPPER BILL OF MATERIALS

Table A.4 – Gripper Bill of Materials

Part Description	Part Number	Vendor	Material Cost	Machining Cost*	Part Cost / Unit	Quantity	Prototype Cost
Lead Screw	17-070-25-20	PIC Inc.	\$2.00	\$12.50	\$14.50	1	\$14.50
Moving Plate			\$5.30	\$50.00	\$55.30	1	\$55.30
Gripper Motor Plate			\$5.30	\$25.00	\$30.30	1	\$30.30
Differential Plate			\$5.30	\$25.00	\$30.30	1	\$30.30
Palm			\$5.30	\$50.00	\$55.30	1	\$55.30
Side Plates for Gripper Motor/Fingers Housing			\$2.00	\$18.75	\$20.75	2	\$41.50
Spacer betwn. Diff. Gear and Wrist Motor			\$0.35	\$12.50	\$12.85	1	\$12.85
1.75" Finger Link			\$0.32	\$6.25	\$6.57	3	\$19.71
1.00" Finger Link			\$0.16	\$6.25	\$6.41	3	\$19.23
Iso-triangular Finger Link			\$1.60	\$18.75	\$20.35	3	\$61.05
Straight Middle Finger Link			\$1.60	\$18.75	\$20.35	3	\$61.05
Finger Tips			\$1.60	\$18.75	\$20.35	3	\$61.05
Torsional Springs for Gripper Fingers			\$0.05		\$0.05	3	\$0.15
Motor Bit			\$1.60	\$18.75	\$20.35	1	\$20.35
Screwdriver Motor/Gearbox	#9072	Black & Decker			\$14.99	1	\$14.99
Thrust Bearing for Gripper	A727M0512	Stock Drive Products			\$5.00	1	\$5.00
Pins, 1.5 ft used	S121M2150	Stock Drive Products			\$2.75	1.5	\$4.13
Retaining Clips	A7X 1-0424A	Stock Drive Products			\$0.15	50	\$7.50
Screws, Nuts, Bolts, Washers					\$10.00	1	\$10.00
Subtotal			\$45.14				\$524.26

* Machining was estimated at \$25/hr

A.3 - CONTROLS BILL OF MATERIALS

Table A.5 – Controls Bill of Materials

Part Description	Part Number	Vendor	Part Cost / Unit	Quantity	Prototype Cost
12V Motor Control Board	MC6-12	Diverse Electronics	\$55.00	5	\$275.00
24V Motor Control Board	MC6-24	Diverse Electronics	\$55.00	1	\$55.00
8 Position Joystick		Radio Shack	\$18.00	1	\$18.00
Switches		Radio Shack	\$1.49	3	\$4.47
3.6V Black & Decker Screwdriver Motor	Model # VP750	Black and Decker	\$19.97	1	\$19.97
2.4V Black & Decker Screwdriver Motor	Model # 9072	Black and Decker	\$14.99	1	\$14.99
24V Motor		Diverse Electronics	\$10.00	1	\$10.00
12V Car Window Motor		Mendelson Liquidation	\$12.50	1	\$12.50
12V Wrist Motors	GM8724S027	Pittman Co.	\$150.22	2	\$300.44
OOPic	OOPic	Reynolds Electronics	\$39.00	2	\$78.00
Wire		Radio Shack	\$7.99	1	\$7.99
10K Resistors		Radio Shack	\$0.10	7	\$0.69
U-shaped Pin Connectors		Radio Shack	\$0.09		\$0.00
Quick Disconnects		Radio Shack	\$0.15		\$0.00
Breakout Boards		Radio Shack	\$3.49	2	\$6.98
Prototyping Boards		Radio Shack	\$21.99	1	\$21.99
Terminal Posts		Digikey			\$0.00
14 Pin Ribbon		Radio Shack	\$1.33	1	\$1.33
5 Pin Connectors	WM2003-ND	Digikey	\$0.35	1	\$0.35
2 Pin Connectors	WM2000-ND	Digikey	\$0.25	1	\$0.25
Crimp Terminals	WM2200-ND	Digikey	\$0.18	1	\$0.18
Subtotal			\$412.09		\$828.13

A.4 - SUMMARIZED COST OF ARM

Table A.6 – Summarized Cost of Arm

Subassembly	Prototype Cost
Base, Lower Arm, and Forearm	\$3605.78
Gripper	\$524.26
Controls	\$828.13
Subtotal	\$4958.17

A.5 - SUPPLIER INFORMATION

Table A.7 – Supplier Information

Company Name	Bearing Distributors, Inc.	Pittman	Stock Drive Products / Sterling Instrument	PIC Design	McMaster-Carr
Contact Person / Sales Rep.	Branch # 52 (Dayton): Mitchell Niese, Branch Manager / Joe Batdorf, Office Manager		OH Sales Representative: ROCKFORD CONTROLS OHIO	OH Sales Representative: JOHN O. OLSEN CO.	
Address	1436 Cincinnati St. (45408) P.O. Box 761	343 Godshall Drive	815 W. Liberty	2017A Lublin Drive	P.O. 94930
	Dayton, OH 45401-0761	Harleysville, PA 19438-0003	Medina, OH 44258	Reynoldsburg, OH 43068	Cleveland, OH 44101-4930
Phone Number	Phone: (513) 224-1537	Phone: (215) 256-6601 or 1-877-748-8626	Phone: (800) 572-0479	Phone: (614) 861-2776 or (800) 270-1107	Phone: (330)995-5500
Fax Number	FAX: (513) 224-5868	Fax: 215-256-1338	Fax: (330) 723-2012	FAX: (614) 861-2776	Fax: (330) 995-9600
E-Mail	dayton@bdi-usa.com	info@pittmannet.com	rockford@ohio.net		cle.sales@mcmaster.com
Web Site	www.bdi-usa.com	www.pittmannet.com	www.sdp-si.com	www.pic-design.com	www.mcmaster.com

Company Name	Diverse Electronic Services	Savage Innovations
Contact Person / Sales Rep.	Carl Kollar	
Address	1202 Gemini Street	
	Nanticoke, PA 18634-3306	
Phone Number	Phone: (570) 735-5053	
Fax Number		Fax: (603) 691-7688
E-Mail	carlk3jml@bigfoot.com	SavageInnovations@OOPic.com
Web Site	members.tripod.com/~divelec/	www.OOPic.com

APPENDIX B

B.1 TORQUE CALCULATIONS

This section consists of the torque calculations for motor and gearing requirements. The initial calculations were determined using revised weights and measurements from the 1999-2000 teams design. These calculations were then updated as the design progressed and changed. The calculations take into consideration the length, center of gravity, and weight for each part of the arm. These calculations are somewhat approximated but accurate enough for motor and gear selection.

Weights (lbs)		Lengths (in)	
A	15.0	a	5
B	4.00	b	25.5
C	3.00	c	33.0
		x	15.50
		y	14.56

Weights (lbs)		Lengths (in)	
B	4.00	b-x	10.0
C	3.00	c-x	17.5

Shoulder	Motor	494.0	lb-in
Elbow	Motor	214.0	lb-in

$$\begin{aligned}\text{Application Factor} &= 1.5 \\ \text{Load} &= 3.3 \text{ lbs}\end{aligned}$$

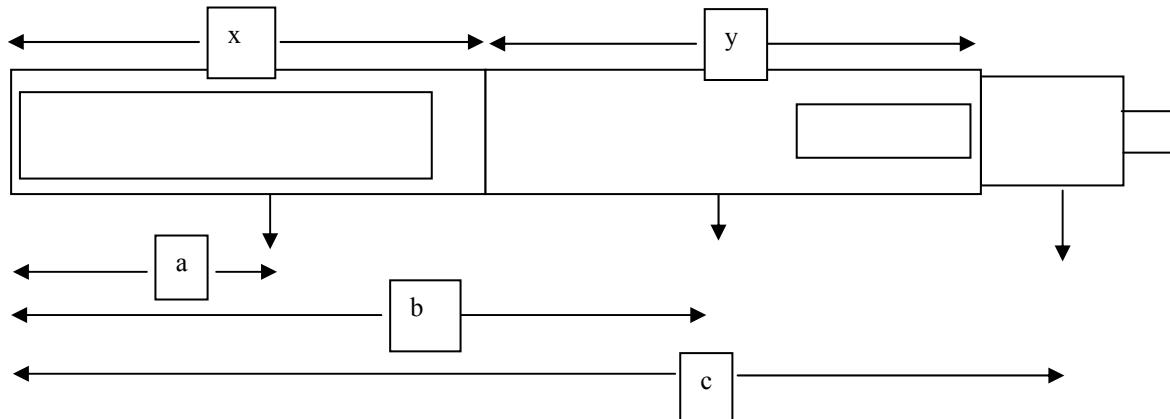


Figure B.1 – Schematic for torque calculations.

B.2 GEAR RATIO CALCULATIONS FOR FIRESTORM 18V DRILL MOTOR

Necessary Dimensions:

1st Stage

Gear	Material	# of Teeth	Diameter (mm)
Sun	Metal	18	14
Planet (3)	Metal	15	12
Ring	Metal	48	34

2nd Stage

Gear	Material	# of Teeth	Diameter (mm)
Sun	Metal	21	16
Planet (3)	Plastic	12	10
Ring	Plastic	45	34

3rd Stage

Gear	Material	# of Teeth	Diameter (mm)
Sun	Metal	12	10
Planet (3)	Metal	18	15
Ring	Metal	48	34

Important Equations:

$$1. \ N_{ring} = N_{sun} + 2N_{planet}$$

where:

N_{planet} = # of teeth on the planet gear

N_{ring} = # of teeth on the ring gear

N_{sun} = # of teeth on the sun gear

$$2. \frac{\varpi_{planet} - \varpi_{arm}}{\varpi_{sun} - \varpi_{arm}} = -\frac{N_{sun}}{N_{planet}}$$

where:

ϖ_{planet} = Rotational speed of planet gear

ϖ_{arm} = Rotational speed of arm gear

ϖ_{sun} = Rotational speed of sun gear

$$3. \frac{\varpi_{ring} - \varpi_{arm}}{\varpi_{sun} - \varpi_{arm}} = -\frac{N_{sun}}{N_{ring}}$$

1st Stage Calculations:

From motor literature operational speed of motor: 10702rpm

$$\varpi_{arm} = \frac{N_{sun} * \varpi_{sun}}{N_{ring} + N_{sun}} \quad (\text{since } \varpi_{ring} = 0)$$

$$\varpi_{arm} = \frac{18\text{teeth} * 10702\text{rpm}}{(48+18)\text{teeth}} = 2918.73\text{rpm}$$

2nd Stage Calculations:

ϖ_{arm} becomes ϖ_{sun2} in the next set of calculations

$$\varpi_{arm2} = \frac{N_{sun}\varpi_{sun2}}{N_{ring1} + N_{sun}}$$

$$\varpi_{arm2} = \frac{21\text{teeth} * 2918.73\text{rpm}}{(45+21)\text{teeth}} = 928.7\text{rpm}$$

3rd Stage Calculations:

ϖ_{arm2} becomes ϖ_{sun3} in the next set of calculations

$$\varpi_{arm3} = \frac{N_{sun}\varpi_{sun3}}{N_{ring2} + N_{sun}}$$

$$\omega_{arm2} = \frac{12\text{teeth} * 928.7\text{rpm}}{(48+12)\text{teeth}} = 185.74\text{rpm}$$

Gear Ratio:

$$\begin{aligned} \text{Gear Ratio} &= \frac{\text{Input speed}}{\text{Output speed}} \\ \text{Gear Ratio} &= \frac{10702\text{rpm}}{185.74\text{rpm}} = \boxed{57.6 : 1} \end{aligned}$$

Power loss in Gear Train of Firestorm 18V drill:

Input power from motor:

$$Power = \frac{Tn}{9549}$$

where:

T = Motor torque in Nm
n = Motor speed in RPM

$$Power = \frac{0.40126\text{Nm} * 10702\text{rpm}}{9549} = .45\text{kW} \rightarrow 450\text{W}$$

The resultant force between the sun and planet gears, F_s , can be calculated at each mesh assuming 2% losses per mesh. A free body diagram of the gear train is displayed in Figure B.2. From static analysis of this diagram the relationship between the force F_s and the force transferred to the arm, F_a . The relationships for F_s and F_a are as follows:

$$F_s = \frac{T_s}{r_s}(0.98)$$

where:

T_s = Torque in the sun gear
 r_s = Sun gear radius

$$F_a = 2F_s$$

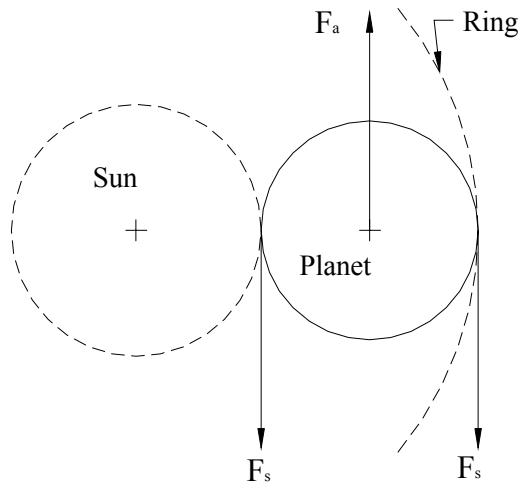


Figure B.2 – Planetary Gear Train Free Body Diagram

We calculate that 1.24Nm is transferred to the 2nd sun gear, 3.63Nm is transferred to the 3rd sun gear, and that the output torque is 13.5Nm. Since the output speed is 185.74 rpm, the power at the exit of the gearbox is 263 Watts.

$$\eta = \frac{\text{Output power}}{\text{Input power}} = \frac{263W}{450W} = 0.584 * 100 = 58.4\% \text{ efficient}$$

APPENDIX C

C.1 KINEMATICS

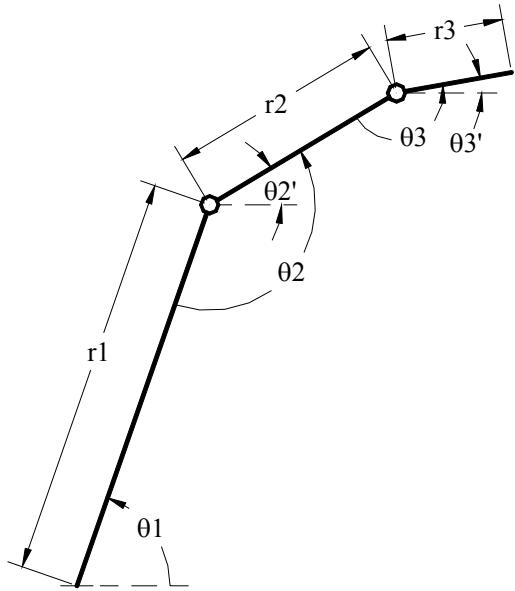


Figure C.1 – Kinematic Model

In the linkage displayed in the figure the links are represented by lengths r_1 , r_2 and r_3 . These lengths correspond to the link lengths of the arm where r_1 is the length of the lower arm, r_2 is the length of the forearm, and r_3 is the length of the gripper. The angles θ_1 , θ_2' , θ_3' represent the angles of the links from the horizontal. Furthermore angle θ_2 represents the angle between link 1 and 2, and θ_3 represents the angle between links 2 and 3. The kinematics analysis is detailed in the following paragraphs and equations.

The following relationships were determined by analyzing the geometry of the linkage:

$$1) \Theta'_2 = \Theta_1 + \Theta_2 + 180^\circ$$

$$2) \Theta'_3 = \Theta'_2 + \Theta_3 + 180^\circ = \Theta_1 + \Theta_2 + \Theta_3$$

The position of the end of link 3, i.e. the tip of the gripper, was evaluated analytically using open-loop kinematic analysis of the linkage. In the following equation x is the position of the gripper in the horizontal direction:

$$3) x = r_1 \cos(\Theta_1) + r_2 \cos(\Theta'_2) + r_3 \cos(\Theta'_3)$$

Equations (1) and (2) were substituted into equation (3) to obtain position equations in terms of the angles between the links instead of from the horizontal. In the following equations y represents the position of the end of link 3 in the vertical direction:

$$4) x = r_1 \cos(\Theta_1) - r_2 \cos(\Theta_1 + \Theta_2) + r_3 \cos(\Theta_1 + \Theta_2 + \Theta_3)$$

$$5) y = r_1 \sin(\Theta_1) - r_2 \sin(\Theta_1 + \Theta_2) + r_3 \sin(\Theta_1 + \Theta_2 + \Theta_3)$$

An assumption was made that angle θ_3' must remain constant. Equation (2) was then differentiated, yielding the following equation:

$$6) \dot{\Theta}'_3 = \dot{\Theta}_1 + \dot{\Theta}_2 + \dot{\Theta}_3 = 0$$

Solving (6) for the derivative of θ_3 yielded the following relationship:

$$7) \dot{\Theta}_3 = -(\dot{\Theta}_1 + \dot{\Theta}_2)$$

Equations (4) and (5) were then differentiated, incorporating the simplifications from (6) and (7). This yielded the following equations:

$$8) \dot{x} = -r_1 \dot{\Theta}_1 \sin(\Theta_1) + r_2 (\dot{\Theta}_1 + \dot{\Theta}_2) \sin(\Theta_1 + \Theta_2)$$

$$9) \dot{y} = r_1 \dot{\Theta}_1 \cos(\Theta_1) - r_2 (\dot{\Theta}_1 + \dot{\Theta}_2) \cos(\Theta_1 + \Theta_2)$$

Equations (8) and (9) were rearranged as follow:

$$10) \dot{\Theta}_2 = \frac{\dot{x} + r_1 \dot{\Theta}_1 \sin(\Theta_1) - r_2 \dot{\Theta}_1 \cos(\Theta_1 + \Theta_2)}{r_2 \cos(\Theta_1 + \Theta_2)}$$

$$11) \dot{\Theta}_2 = \frac{-\dot{y} + r_1 \dot{\Theta}_1 \cos(\Theta_1) - r_2 \dot{\Theta}_1 \cos(\Theta_1 + \Theta_2)}{r_2 \cos(\Theta_1 + \Theta_2)}$$

Finally equations (10) and (11) were set equal to each other and solved for the derivative of angle Θ_1 . The equation is as follows:

$$12) \dot{\Theta}_1 = \frac{\dot{x} \cos(\Theta_1 + \Theta_2) + \dot{y} \sin(\Theta_1 + \Theta_2)}{r_1 [\cos(\Theta_1 + \Theta_2) \sin(\Theta_1) + \sin(\Theta_1 + \Theta_2) \cos(\Theta_1)]}$$

C.2 MASTER OOPIC CONTROL CODE

```
// MASTER CODE FOR CONTROL OF THE ARM
//
// FILE NAME:  MASTER_1
// CREATED:  5/08/01
// LAST MODIFIED:  5/29/01
// AUTHORS:  MICHAEL STEVENS AND AARON WEAVER
//
// NOTES:  THIS CODE WILL OPERATE THE ARM
//          USING FOUR DIRECTIONS ON THE
//          JOYSTICK.  ANOTHER OOPIC WILL BE USED TO
//          OPERATE THE WRIST.  MODES OF COMMUNICATION
//          WILL BE SENT FROM THIS MASTER CODE TO THE
//          SLAVE VIA I/O LINES.
//
// MOTORS ARE NUMBERED AS FOLLOWS:
//      #1 = SHOULDER BEND
//      #2 = SHOULDER TWIST
//      #3 = ELBOW BEND
//      #4 & #5 = FOREARM
//      #6 = GRIPPER

opwm pwm1 = new opwm;           // PWM #1, for m3 & m6
opwm pwm2 = new opwm;           // PWM #2, for m1 & m2
odiol m1f = new odiol;          // Motor #1 forward line
odiol m1e = new odiol;          // Motor #1 enable line
odiol m1b = new odiol;          // Motor #1 backward line
odiol m2f = new odiol;          // Motor #2 forward line
odiol m2e = new odiol;          // Motor #2 enable line
odiol m2b = new odiol;          // Motor #2 backward line
odiol m3f = new odiol;          // Motor #3 forward line
odiol m3e = new odiol;          // Motor #3 enable line
odiol m3b = new odiol;          // Motor #3 backward line
odiol m6f = new odiol;          // Motor #6 forward line
odiol m6e = new odiol;          // Motor #6 enable line
odiol m6b = new odiol;          // Motor #6 backward line
odiol jf = new odiol;           // Joystick forward line
odiol jb = new odiol;           // Joystick backward line
odiol jl = new odiol;           // Joystick left line
odiol jr = new odiol;           // Joystick right line
ogate jfgate = new ogate;       // Gate to link jfgo to jf
ogate jbgate = new ogate;       // Gate to link jbgo to jb
ogate jlgate = new ogate;       // Gate to link jlgo to jl
ogate jrgate = new ogate;       // Gate to link jrgo to jr
oevent jfgo = new oevent;        // Event for joystick forward
oevent jbgo = new oevent;        // Event for joystick backward
oevent jlgo = new oevent;        // Event for joystick left
oevent jrgo = new oevent;        // Event for joystick right
odiol s1 = new odiol;            // Switch #1
odiol s2 = new odiol;            // Switch #2
odiol s3 = new odiol;            // Switch #3
odiol wf = new odiol;           // Command SLAVE to bend wrist forward
odiol wb = new odiol;           // Command SLAVE to bend wrist backward
odiol wl = new odiol;           // Command SLAVE to twist wrist left
odiol wr = new odiol;           // Command SLAVE to twist wrist right
obit nogo = new obit;

sub void main(void)
```

```

{
pwm1.ioline = 17;
pwm1.prescale = 3;
pwm1.period = 255;
pwm1.operate = 1;
pwm1.value = 0;
pwm2.ioline = 18;
pwm2.prescale = 3;
pwm2.period = 255;
pwm2.operate = 1;
pwm2.value = 0;

m1f.ioline = 31;
m1f.direction = cvoutput;
m1b.ioline = 30;
m1b.direction = cvoutput;
m1e.ioline = 29;
m1e.direction = cvoutput;

m2f.ioline = 28;
m2f.direction = cvoutput;
m2b.ioline = 27;
m2b.direction = cvoutput;
m2e.ioline = 26;
m2e.direction = cvoutput;

m3f.ioline = 25;
m3f.direction = cvoutput;
m3b.ioline = 24;
m3b.direction = cvoutput;
m3e.ioline = 23;
m3e.direction = cvoutput;

wf.ioline = 5;
wf.direction = cvoutput;
wb.ioline = 4;
wb.direction = cvoutput;
wl.ioline = 7;
wl.direction = cvoutput;
wr.ioline = 6;
wr.direction = cvoutput;

m6f.ioline = 3;
m6f.direction = cvoutput;
m6b.ioline = 2;
m6b.direction = cvoutput;
m6e.ioline = 1;
m6e.direction = cvoutput;

jf.ioline = 13;
jf.direction = cvinput;
jb.ioline = 14;
jb.direction = cvinput;
jl.ioline = 12;
jl.direction = cvinput;
jr.ioline = 11;
jr.direction = cvinput;

s1.ioline = 8;
s1.direction = cvinput;
s2.ioline = 9;
s2.direction = cvinput;
s3.ioline = 10;

```

```

s3.direction = cvinput;

m1f.value = 0;
m1b.value = 0;
mle.value = 0;
m2f.value = 0;
m2b.value = 0;
m2e.value = 0;
m3f.value = 0;
m3b.value = 0;
m3e.value = 0;
wf.value = 0;
wb.value = 0;
wl.value = 0;
wr.value = 0;
m6f.value = 0;
m6b.value = 0;
m6e.value = 0;

jfgate.input1.link(jf);
jfgate.invertout = 1;
jfgate.output.link(jfgo);
jfgate.operate = 1;
jbgate.input1.link(jb);
jbgate.invertout = 1;
jbgate.output.link(jbgo);
jbgate.operate = 1;
jlgate.input1.link(jl);
jlgate.invertout = 1;
jlgate.output.link(jlgo);
jlgate.operate = 1;
jrgate.input1.link(jr);
jrgate.invertout = 1;
jrgate.output.link(jrgo);
jrgate.operate = 1;

}

///////////////////////////////
// Joystick forward
Sub void jfgo_code(void)
{
nogo = 0;
if (s1.value & s2.value)
{
  nogo = 1;
}
if (s1.value & s3.value)
{
  nogo = 1;
}
if (s2.value & s3.value)
{
  nogo = 1;
}
if (nogo == 0)
{
  if (s1.value)
  {
    mlf.value = 1;
    mle.value = 1;
    do
    {

```

```

pwm2.value = 153;
wb.value = 1;
} while (jf == 0);
pwm2.value = 10;
OOPic.delay = 20;
pwm2.value = 0;
mlf.value = 0;
mle.value = 0;
wb.value = 0;
}
if (s2.value)
{
m3f.value = 1;
m3e.value = 1;
pwm1.value = 30;
OOPic.delay = 10;
do
{
pwm1.value = 90;
wb.value = 1;
} while (jf == 0);
pwm1.value = 10;
OOPic.delay = 20;
pwm1.value = 0;
m3f.value = 0;
m3e.value = 0;
wb.value = 0;
}
if (s3.value)
{
m6f.value = 1;
m6e.value = 1;
pwm1.value = 30;
OOPic.delay = 10;
do
{
pwm1.value = 90;
} while (jf == 0);
pwm1.value = 10;
OOPic.delay = 20;
pwm1.value = 0;
m6f.value = 0;
m6e.value = 0;
}
}

// Joystick back
Sub void jbgo_code(void)
{
nogo = 0;
if (s1.value & s2.value)
{
nogo = 1;
}
if (s1.value & s3.value)
{
nogo = 1;
}
if (s2.value & s3.value)
{
nogo = 1;
}
}

```

```

if (nogo == 0)
{
    if (s1.value)
    {
        m1b.value = 1;
        m1e.value = 1;
        do
        {
            pwm2.value = 153;
            wf.value = 1;
        } while (jb == 0);
        pwm2.value = 10;
        OOPic.delay = 20;
        pwm2.value = 0;
        m1b.value = 0;
        m1e.value = 0;
        wf.value = 0;
    }
    if (s2.value)
    {
        m3b.value = 1;
        m3e.value = 1;
        pwml.value = 30;
        OOPic.delay = 10;
        do
        {
            pwml.value = 90;
            wf.value = 1;
        } while (jb == 0);
        pwml.value = 10;
        OOPic.delay = 20;
        pwml.value = 0;
        m3b.value = 0;
        m3e.value = 0;
        wf.value = 0;
    }
    if (s3.value)
    {
        m6b.value = 1;
        m6e.value = 1;
        pwml.value = 30;
        OOPic.delay = 10;
        do
        {
            pwml.value = 90;
        } while (jb == 0);
        pwml.value = 10;
        OOPic.delay = 20;
        pwml.value = 0;
        m6b.value = 0;
        m6e.value = 0;
    }
}

// Joystick left
Sub void jlgo_code(void)
{
    nogo = 0;
    if (s1.value & s2.value)
    {
        nogo = 1;
    }
}

```

```

if (s1.value & s3.value)
{
    nogo = 1;
}
if (s2.value & s3.value)
{
    nogo = 1;
}
if (nogo == 0)
{
    if (s1.value)
    {
        m2f.value = 1;
        m2e.value = 1;
        pwm2.value = 30;
        OOPic.delay = 5;
        do
        {
            pwm2.value = 90;
        } while (jl == 0);
        pwm2.value = 10;
        OOPic.delay = 20;
        pwm2.value = 0;
        m2f.value = 0;
        m2e.value = 0;
    }
    if (s2.value)
    {
        do
        {
            wb.value = 1;
        } while (jl == 0);
        wb.value = 0;
    }
    if (s3.value)
    {
        do
        {
            wl.value = 1;
        } while (jl == 0);
        wl.value = 0;
    }
}
}

```

```

// Joystick right
Sub void jrgo_code(void)
{
nogo = 0;
if (s1.value & s2.value)
{
    nogo = 1;
}
if (s1.value & s3.value)
{
    nogo = 1;
}
if (s2.value & s3.value)
{
    nogo = 1;
}
if (nogo == 0)
{

```

```
if (s1.value)
{
    m2b.value = 1;
    m2e.value = 1;
    pwm2.value = 35;
    OOPic.delay = 10;
    do
    {
        pwm2.value = 80;
    } while (jr == 0);
    pwm2.value = 10;
    OOPic.delay = 20;
    pwm2.value = 0;
    m2b.value = 0;
    m2e.value = 0;
}
if (s2.value)
{
    do
    {
        wf.value = 1;
    } while (jr == 0);
    wf.value = 0;
}
if (s3.value)
{
    do
    {
        wr.value = 1;
    } while (jr == 0);
    wr.value = 0;
}
}
```

C.3 SLAVE OOPIC CONTROL CODE

```
// SLAVE CODE FOR CONTROL OF THE ARM
//
// DATE: 5/08/01
// LAST MODIFIED: 5/29/01
// AUTHORS: MICHAEL STEVENS AND AARON WEAVER

opwm pwm3 = new opwm;           // PWM #3, for m4
opwm pwm4 = new opwm;           // PWM #4, for m5
odiol1 wf = new odiol1;         // Command from MASTER to bend wrist forward
odiol1 wb = new odiol1;         // Command from MASTER to bend wrist backward
odiol1 wl = new odiol1;         // Command from MASTER to twist wrist left
odiol1 wr = new odiol1;         // Command from MASTER to twist wrist right
odiol1 m4f = new odiol1;         // Motor #4 forward line
odiol1 m4e = new odiol1;         // Motor #4 enable line
odiol1 m4b = new odiol1;         // Motor #4 backward line
odiol1 m5f = new odiol1;         // Motor #5 forward line
odiol1 m5e = new odiol1;         // Motor #5 enable line
odiol1 m5b = new odiol1;         // Motor #5 backward line
ogate wfgate = new ogate;       // Gate to link wfgo to wf
ogate wbgate = new ogate;       // Gate to link wbgo to wb
ogate wlgate = new ogate;       // Gate to link wlgo to wl
ogate wrgate = new ogate;       // Gate to link wrgo to wr
oevent wfgo = new oevent;        // Event for wrist bend forward
oevent wbgo = new oevent;        // Event for wrist bend backward
oevent wlgo = new oevent;        // Event for wrist bend left
oevent wrgo = new oevent;        // Event for wrist bend right

sub void main(void)
{
wf.ioline = 5;
wf.direction = cvinput;
wb.ioline = 4;
wb.direction = cvinput;
wl.ioline = 7;
wl.direction = cvinput;
wr.ioline = 6;
wr.direction = cvinput;

pwm3.ioline = 17;
pwm3.prescale = 3;
pwm3.period = 255;
pwm3.operate = 1;
pwm3.value = 0;
pwm4.ioline = 18;
pwm4.prescale = 3;
pwm4.period = 255;
pwm4.operate = 1;
pwm4.value = 0;

m4f.ioline = 31;
m4f.direction = cvoutput;
m4b.ioline = 30;
m4b.direction = cvoutput;
m4e.ioline = 29;
m4e.direction = cvoutput;

m5f.ioline = 28;
m5f.direction = cvoutput;
```

```

m5b.ioline = 27;
m5b.direction = cvoutput;
m5e.ioline = 26;
m5e.direction = cvoutput;

wfgate.input1.link(wf);
wfgate.output.link(wfgo);
wfgate.operate = 1;
wbgate.input1.link(wb);
wbgate.output.link(wbgo);
wbgate.operate = 1;
wlgate.input1.link(wl);
wlgate.output.link(wlgo);
wlgate.operate = 1;
wrgate.input1.link(wr);
wrgate.output.link(wrgo);
wrgate.operate = 1;

}

///////////////////////////////
// Wrist bend forward
Sub void wfgo_code(void)
{
m4f.value = 1;
m4e.value = 1;
m5f.value = 1;
m5e.value = 1;
do
{
pwm3.value = 102;
pwm4.value = 102;
} while (wf == 1);
pwm3.value = 10;
pwm4.value = 10;
OOPic.delay = 20;
pwm3.value = 0;
pwm4.value = 0;
m4f.value = 0;
m4e.value = 0;
m5f.value = 0;
m5e.value = 0;
}

// Wrist bend backward
Sub void wbgo_code(void)
{
m4b.value = 1;
m4e.value = 1;
m5b.value = 1;
m5e.value = 1;
do
{
pwm3.value = 102;
pwm4.value = 102;
} while (wb == 1);
pwm3.value = 10;
pwm4.value = 10;
OOPic.delay = 20;
pwm3.value = 0;
pwm4.value = 0;
m4b.value = 0;
m4e.value = 0;
}

```

```

m5b.value = 0;
m5e.value = 0;
}

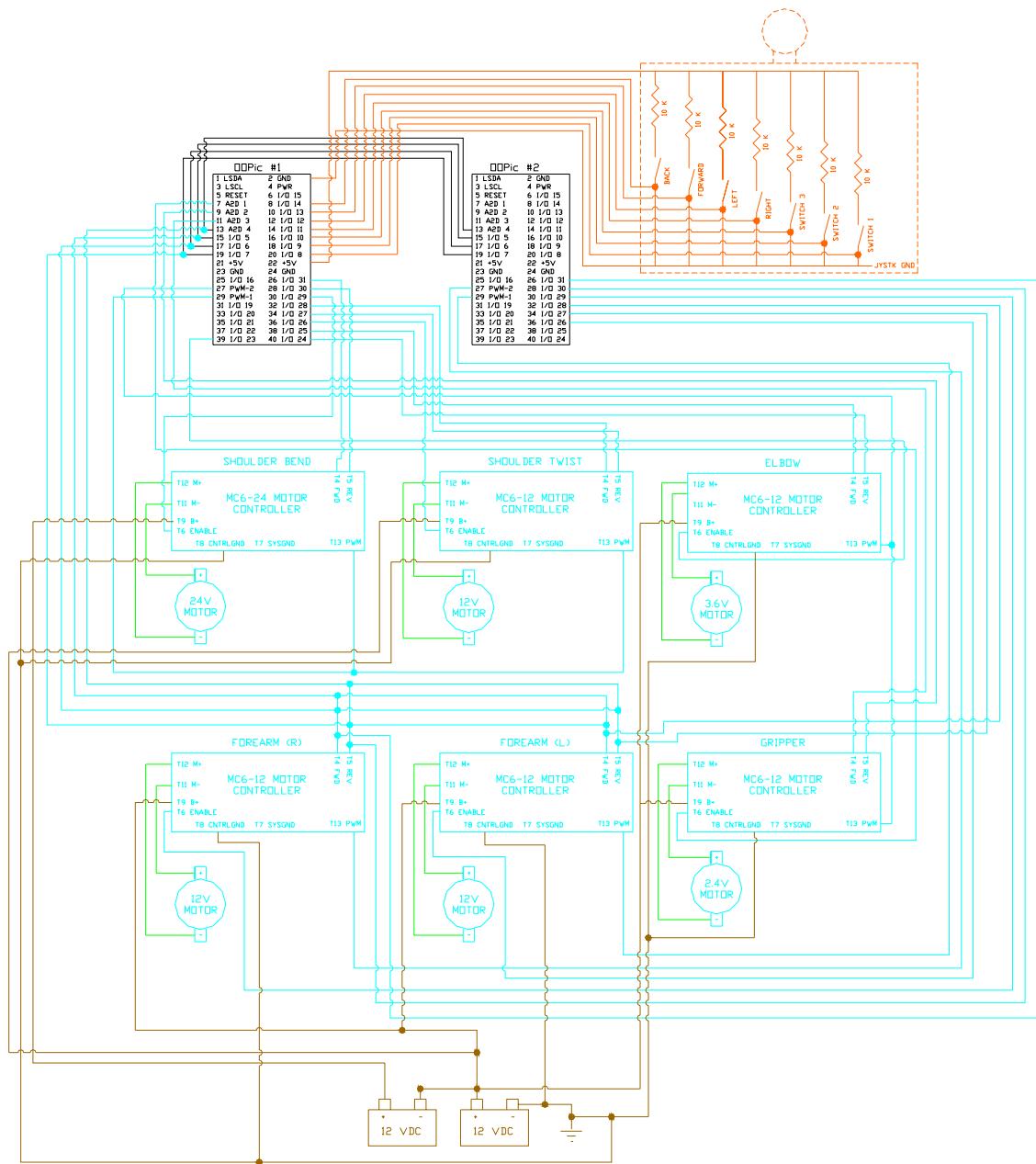
// Wrist twist left
Sub void wlgo_code(void)
{
m4f.value = 1;
m4e.value = 1;
m5b.value = 1;
m5e.value = 1;
do
{
    pwm3.value = 102;
    pwm4.value = 102;
} while (wl == 1);
pwm3.value = 10;
pwm4.value = 10;
OOPic.delay = 20;
pwm3.value = 0;
pwm4.value = 0;
m4f.value = 0;
m4e.value = 0;
m5b.value = 0;
m5e.value = 0;
}

// Wrist twist right
Sub void wrgo_code(void)
{
m4b.value = 1;
m4e.value = 1;
m5f.value = 1;
m5e.value = 1;
do
{
    pwm3.value = 102;
    pwm4.value = 102;
} while (wr == 1);
pwm3.value = 10;
pwm4.value = 10;
OOPic.delay = 20;
pwm3.value = 0;
pwm4.value = 0;
m4b.value = 0;
m4e.value = 0;
m5f.value = 0;
m5e.value = 0;
}

```

APPENDIX D

ELECTRICAL SCHEMATICS



APPENDIX E

E.1 ALTERNATIVE CONTROLS

One member of the design team developed an alternate control scheme, and this control scheme is described in the following sections:

E.2 INTRODUCTION AND GOALS

This alternative control system has been developed in attempt to further lower cost as well as gain some practical knowledge in designing controls for the arm. This chapter includes details on this control system as well as the knowledge gained throughout the controls design.

As mentioned, the first goal of this control system was to reduce cost. It was earlier estimated that the current control system in development would be in the ballpark of \$1000-\$2000 dollars, making the controls cost a significant part of the total cost of the arm. Any reduction in that cost would certainly help with the goal of creating an arm with a practical price tag.

The second goal was simply to have a control system that would operate the arm in its entirety. The arm has 6 degrees of freedom; therefore, the controls need to be able to actuate all 6 degrees without rearranging any wires (hooking and unhooking various joints/motors).

A third goal was to have a control system with variable speed capabilities. Variable speed makes fine-tuned motion easier to operate. It is clear to see how important slow motion is for a manually controlled robotic arm, which may at times be used to do delicate tasks that would be difficult or impossible to do without speed variability.

Finally, a fourth goal was to create a control system that was reasonably easy and intuitive to use. Because this is an interface between a machine and a human being, human factors becomes an important issue. The controls need to make sense, be easy to operate, and perform in a reliable and predictable manner.

E.3 ASSUMPTIONS

Like most design problems, some reasonable assumptions can be made in order to get some clear direction for development. These assumptions turned out to be a crucial part in the shaping of this control system.

The first assumption was that no positional feedback from the arm is required at any joint. Unlike robotic arms used in industry, which are largely completely automated, the wheelchair arm is manually controlled by a human being who can literally see the position of the arm, providing the only positional feedback necessary. This assumption helped to simplify the controls a great deal and reduce cost.

The next assumption was that no motor speed feedback was required, again simplifying the controls. Motor speed feedback (usually in the form of a tachometer) is costly and used mainly for systems that require precision movements. Because this arm is manually operated, the user can see the speed and vary it accordingly.

The final assumption was that the user has limited dexterity in the hands. This is a reasonable assumption because the arm is being designed in the hopes that it can be used by a paraplegic or quadriplegic. Limited hand dexterity, in this case, means that the user is able to control the movement of his/her hand, but may not be able to grip things. As a result, a joystick with yaw control (3-D joystick) would not be a viable option. This limits us mainly to buttons, switch and a 2-axis joystick similar to the one used to control the chair itself.

E.4 CONTROL DESIGN – GENERAL DESCRIPTION

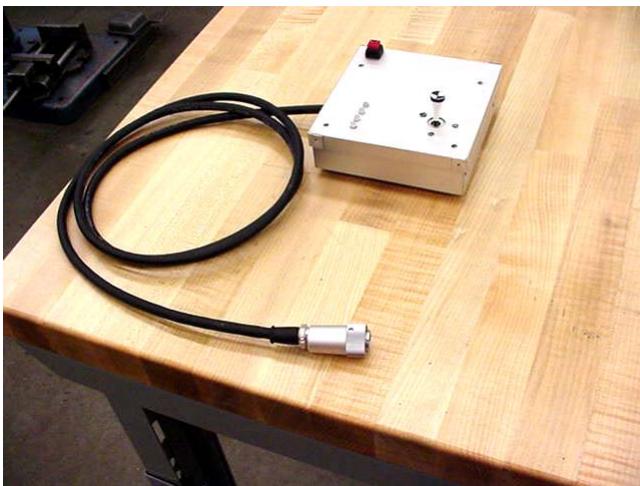


Figure E.1 – Control Box

The controls consist of two systems (not including the motors themselves). There is the actual control module and there is the amplification module. The control module is what the user interfaces with to actuate the arm and the amplification module amplifies the control module signals in order to power the motors.

The user operates the control module with a 2-axis analog joystick which has a built-in button. The x- and y-axis of the joystick are used to allow variable speed control of two different motors in either direction at the same time. The button is used to select one of four available operation modes.

Because the arm has 6 degrees of freedom and the joystick has only two, not all arm motors can be controlled at the same time without the use of a very high-level math processor and some rather complicated programming. To fix this issue, the arm's operation is broken into four different modes, each controlling a different combination of motors/joints. The different modes and their joint combinations are shown below in Table E.1.

Table E.1 – Controller Mode Setup

MODE	JOINT/MOTION	JOYSTICK AXIS
I	Should Twist	X
	Should Bend	Y
2	Should Twist	X
	Elbow Bend	Y
3	Wrist Twist	X
	Wrist Bend	Y
4	Gripper Open/Close	X
	Elbow Bend	Y

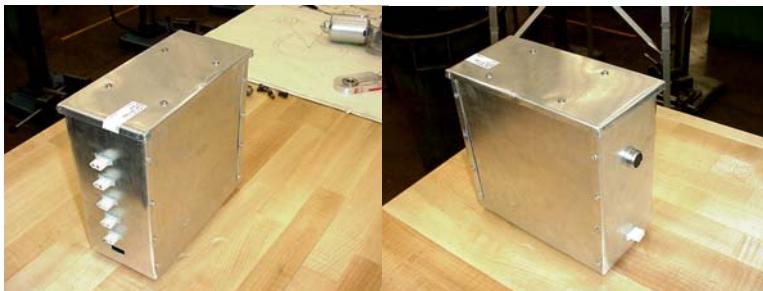


Figure E.2 - Amplifier Box

This control module uses a technique called pulse width modulation or PWM to vary the speed of the motors. This process will be explained in greater detail in the next section. The signals from the control module are amplified by H-bridges

in the amplifier module. This, too, will be explained in the next section.

E.5 CONTROLS DESIGN – DETAILED DESCRIPTION

As mentioned in the previous section, the controls system consists of two modules: the control module and the amplifier module. The two modules are connected with a 10-conductor cable that carries all of the control signals as well as the power supply and common ground for the control module.

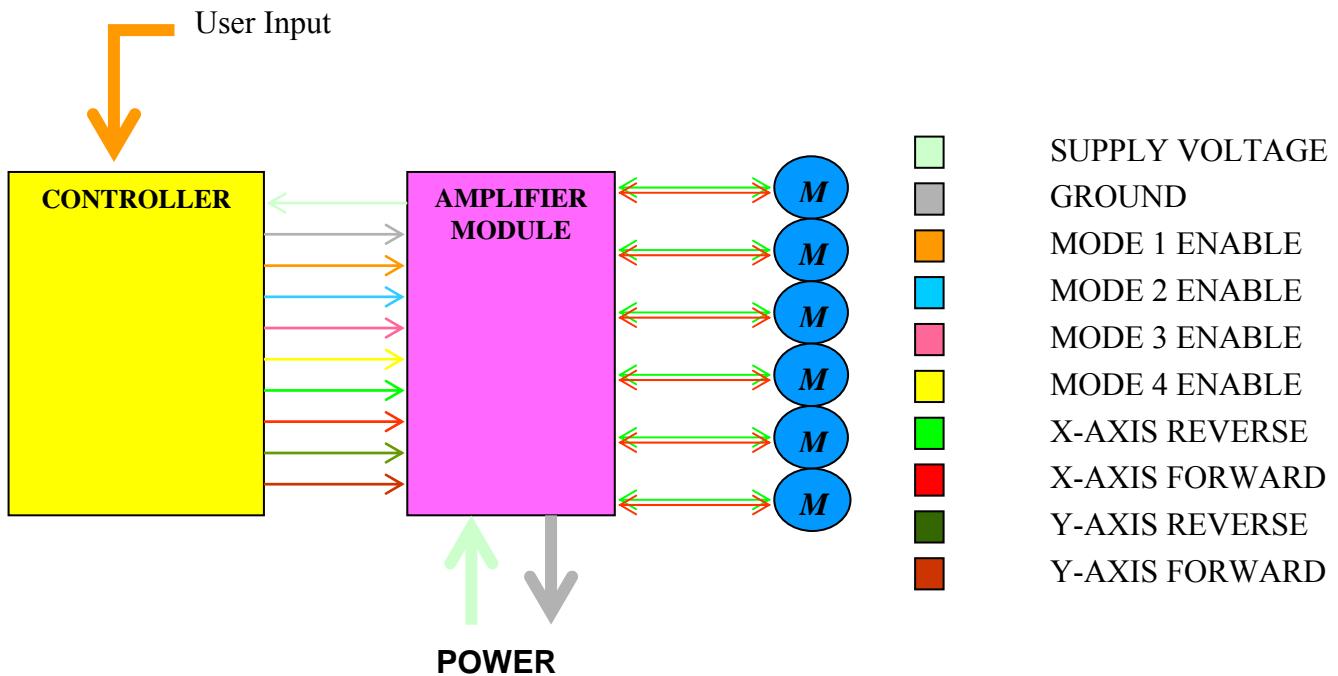


Figure E.3 Basic Signal Flow Chart

The signals going to the amplifier module consist of the mode enable signals, the x-axis forward and reverse and the y-axis forward and reverse. The PWM signal is sent across the forward and reverse lines while a steady logic on/off signal is sent down each of the four mode enable lines. Only one of the four mode lines is on at a time.

The control module houses a custom-made printed circuit board (PCB) which contains the entire control module circuit minus the on/off button located on the box lid. In order to allow for the board's easy removal from the box, all of its input/output lines run to a 9-pin Molex plug which connects to the leads of the outgoing 10-conductor cable. The tenth wire, which is the supply voltage, is routed separately through the power button via two sets of shielded spade connectors.

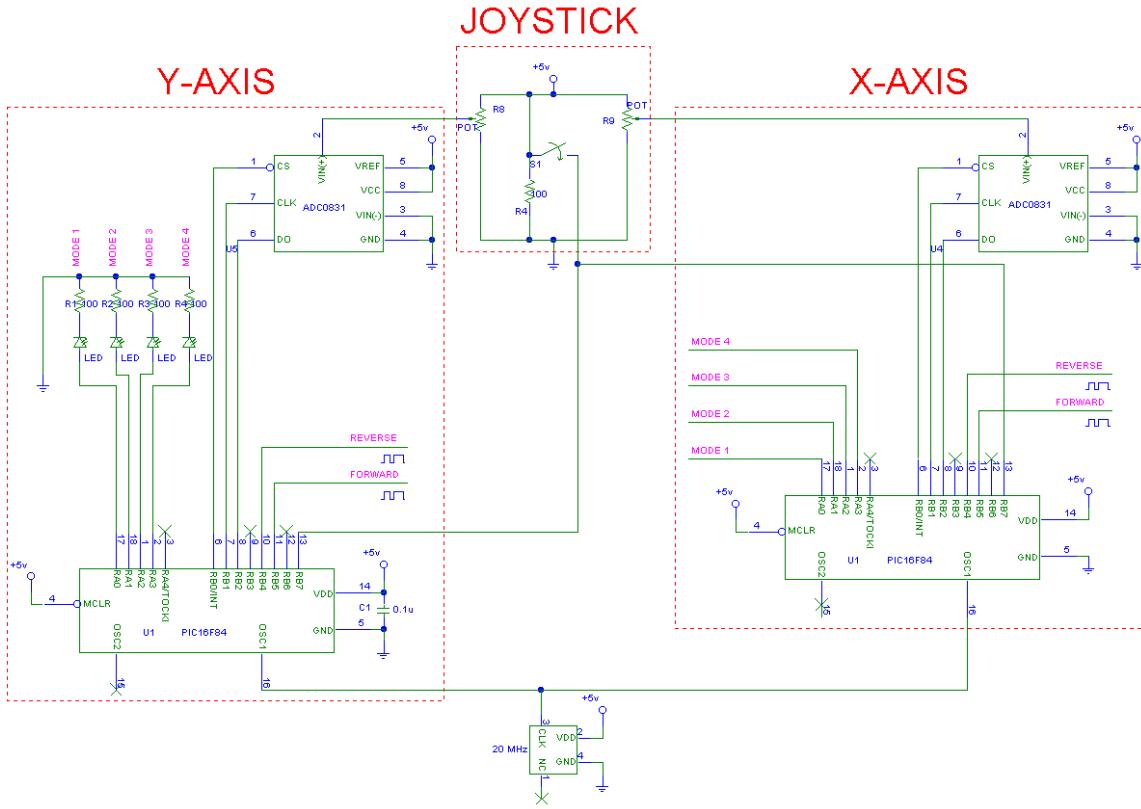


Figure E.4 - Control Circuit Schematic

The circuit in the control module can be broken up into three main parts: the joystick, the x-axis controller and the y-axis controller. Both the x- and y-axis controller contain identical hardware with one exception. The y-axis systems mode enable lines power a set of four LEDs which indicate the current mode selection. In contrast, the x-axis systems enable lines are the very same lines that run down to the amplifier module.

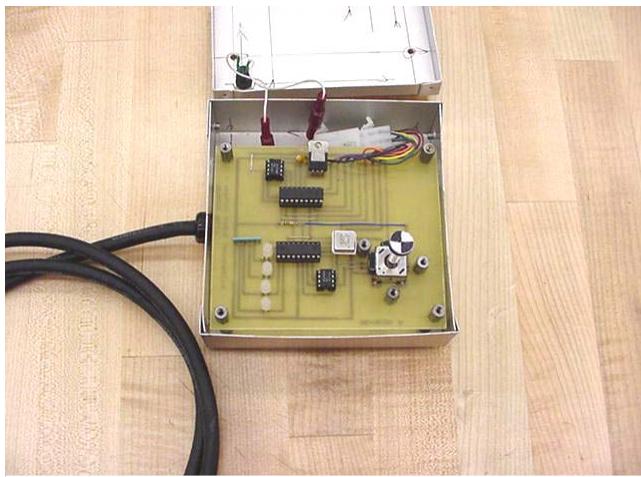


Figure E.5 - Control Module Circuit - Top

The joystick is essentially two $10\text{ k}\Omega$ potentiometers and a normally-off contact switch (push button). Each potentiometer is one axis of motion. A variable output voltage is achieved by applying a low and high reference voltage to the potentiometer. Using its center tap as the output, the potentiometer is varied by moving the joystick. This changes the resistance of the potentiometer and, as a result, varies the

voltage between the low and high reference voltages. This is a very common way of achieving analog control in electronics.

The contact switch built into the joystick is a normally-off switch meaning that it is in the off position until pushed. The difference between a contact switch and a standard button is that a contact switch has less “play” between the on-state and the off-state. With an ordinary button, there is some gray area between on and off. This causes problems with a digital circuit that is trying to interpret whether the switch is sending a high or low signal. This particular contact switch is used to select the desired operating mode. The input lead of the switch is connected to the supply voltage. On the other side of the switch, the output lead goes to the microcontrollers, but at the same time is “pulled low” by a 100Ω resistor. Because the input of the microcontrollers have nearly infinite input impedance there is no current flowing along the output line of the switch. Therefore, when the switch is open, the output is connected to ground through the resistor and is referred to as being “pulled low.” When the switch is closed, the input voltage is passed along to the output and separated from ground by the resistor. This means that the input to the microcontroller is whatever the input voltage to the switch was, making the switch behave like a binary input, high or low.

The supply voltage coming into the control module is the very same supply voltage that runs the amplifier module and, in turn, the motors. The supply comes from the two 12V car batteries hooked in series that are mounted on the wheelchair. This makes a total of 24 volts. However, because the control module is mostly a digital circuit, it is not designed to run at such a high voltage. To remedy this, the 24V supply that is input to the control module is run through the power button straight to a 5V voltage regulator. At is the only thing the supply voltage is connected to. The rest of the circuit is connected to the 5V output of the regulator which provides a nice steady voltage that is more to the digital circuit’s liking. With the help of a small filtering capacitor, the voltage regulator also filters out most of the electrical noise created by the motors.

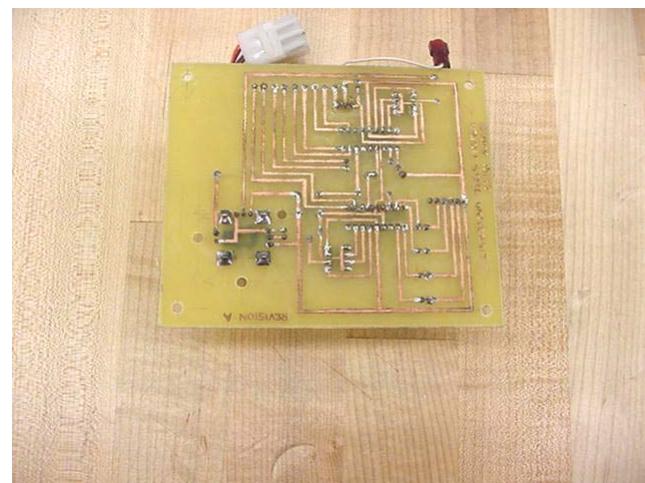


Figure E.6 - Control Module Circuit - Bottom

The x- and y-axis control circuits both consist of a microcontroller, and analog-to-digital converter (ADC), and a single 20MHz clock-oscillator which is shared by both microcontrollers. The microcontroller chose was Microchip Inc's PIC16F84, the 20MHz variety (they also make an older 4 MHz version). The ADC is National Semiconductors ADC0831.

The PIC16F84 is an 8-bit microcontroller that has 13 I/O lines. It has the capability to do simple multitasking with the use of its timer-overflow interrupt feature. The internal clock speed of the chip is $\frac{1}{4}$ the input clock speed. In this case, that means the chip is essentially running at 5 MHz. It is a relatively efficient chip, taking only one cycle to run an instruction with the exception of program branches such as goto's and subroutine calls. One of the most attractive features of this microcontroller is the price. At about \$6 apiece, they provide a good deal of functionality.

The ADC in this control circuit is an 8-bit serial converter. This particular converter uses a conversion technique known as successive approximation. This means that the converter determines one bit at a time, starting with the most significant bit (bit 7) and working down to the least significant bit (bit 0). The process takes about 30 μ s to complete, after which it is ready to output the result. The ADC requires two lines to control. The first line tells the ADC to start the conversion (the CS line). The second line supplies the digital clock signal to the ADC in order to get it to send its output one bit at a time. The ADC also receives a high and low reference voltage to which to compare its analog voltage input. When the conversion process starts, the ADC takes a snapshot of the input analog voltage and compares it to the reference voltages. It then outputs an 8-bit number between 0 and 255 that indicates where the analog voltage is between the reference voltages. For example, if the input is the same as the low reference voltage, then the output would be a binary 0. If the input is half way between the low and high references, then the output would be 127 (half of 255). This give the microcontroller a way to understand where the joystick is positioned.

Before explaining how this circuit works as a whole, it is important to understand the process of pulse width modulation and how the microcontroller counts time. The speed of a DC motor is controlled by voltage, provided that the motor is not approaching its stall current. The spinning of the motor generates a backwards voltage or back EMF (electro-motive force) that works against the input voltage. The faster the motor spins, the more back EMF it generates until the motor reaches a speed where the back EMF and the input voltage are approximately

equal. At this point the motor has reached a stable speed that it will maintain regardless of the load placed on it. This is all assuming that there is (a) enough current available for the motor to draw from and (b) the motor is not approaching its stall current where it will eventually slow down and stop.

Now, there are two ways to control the voltage level being input to the motor. The first is to place a variable resistor in series with the motor at the motor's input. By increasing the resistance, the voltage drop across the resistor increases thereby decreasing the input voltage to the motor. This is a rather inefficient and unreliable means of motor speed control. Plus, it can drastically limit the current being provided to the motor.

The other way to control the motor's input voltage is through a process called pulse width modulation or PWM. PWM is nice because the motor is always supplied with the maximum voltage available. By inputting the voltage in pulses of varied length the effective voltage changes and creates the same response from the motor as applying a constant voltage of the same level as the effective voltage. This is much more efficient than using a variable resistor to change the input voltage and the current delivery capability is limited only by the power source.

The PWM signal consists of two parts the off-time or off-cycle and the on-time or duty-cycle. The off-cycle is the period of time that the pulse is off while the duty-cycle is the period of time that the pulse is on. To determine the effective voltage being generated by the PWM, the formula is

$$\begin{aligned} t_{off} &= \text{off - cycle} \\ t_{on} &= \text{duty - cycle} \\ V_{eff} &= V_{\text{supply}} \left(\frac{t_{on}}{t_{on} + t_{off}} \right) \end{aligned}$$

For the PIC microcontroller to generate a PWM signal, it has to have a way of counting on-time and off-time. This is done by a process called timer interrupt counting. The timer in the microcontroller is an 8-bit register that counts clock cycle (the internal ones, not the external ones). After the timer has counted 256 cycles ($51.2 \mu\text{s}$ total) it overflows back to zero and calls an interrupt. When the interrupt is called, the PIC drops whatever it was doing and goes to the interrupt handler in the code to find out what to do. After the interrupt instructions have been carried out, the PIC returns to where it was before it was interrupted and continues on. This allows for a rudimentary form of multitasking because the PIC can be busy doing other things

while it counts off time. To generate a PWM signal, the PIC has a set off-time of 50 timer interrupts, and it varies the on-time between 10 and 110 timer interrupts depending on the position of the joystick.

How the entire circuit works together to control the arm is explained here. We will still just focus on one axis of motion because the other axis functions the same way. The process starts when the PIC requests a joystick reading from the ADC. After the ADC has finished with the conversion, the PIC begins reading it in one bit at a time. Meanwhile, the PWM is in the last stages of the off-cycle. When the entire conversion is read in, the PIC determines whether the joystick is in reverse, forward or the dead zone. The dead zone is the area where the joystick is centered that is about 1/5 the width of the joystick's entire range of motion (input number will be between 100 and 155). If the joystick is in this location, the PIC produces no duty-cycle, goes back to the beginning of the off-cycle and starts all over again. If the joystick is in reverse, the PIC subtracts the input number (between 0 and 99) from 110 and the result is the length of the duty cycle in timer interrupts. When the joy stick is in the forward position, the PIC subtracts 146 from the input (between 156 and 255) and the result is the length of the duty cycle in timer interrupts.

After determining the duty cycle length, the PIC turns on the forward line for forward or the reverse line for reverse. Notice that only one of these lines can be on at a time. During the duty-cycle, the PIC basically just continues to count down the timer interrupts until the duty-cycle is to end. At the end of the duty-cycle, which ever line was turned on is now turned off and the PIC enters the off-cycle state were it will begin the process all over again.

That procedure goes on indefinitely as long as the controller is turned on. The only exception is when the mode select button is pressed. Like the timer overflow, the button pushing triggers an interrupt. The PIC stops whatever it's doing, shuts off both forward and reverse lines, changes to the next mode, and then stays in pause loop until the button is released. At that point, the PIC returns to the beginning of the off-cycle and goes back to normal operation. The code for both PICs is the identical. It can be found in Section E.7.

The operation and output of the control module is worthless without some way to amplify the signal to a point that is strong enough to actually power the motors. This is the reason behind the amplifier module.

The amplifier module has two major parts: the router board and the H-bridges. The router board does exactly what the name implies; it routes the signals coming from the controller module to the appropriate place. It is a simple device consisting of 12-pin Molex plug for input, a 2-pin power input, and six 3-pin output. All of this is connected with a series of wires tracers and diodes.

The other part of the amplifier module is the part containing amplifiers themselves. The type of amplifier used is called an H-bridge, a device designed specifically for 2-direction motor control. There are six H-bridges, one for each motor. All of the H-bridges were made the same for simplicity sake and all of the components were chosen to be able to handle the largest motor of the lot. All of the H-bridges have one 3-pin input receptacle, two lines to the motor, a supply voltage line and a ground line. This 3-pin input receives and enable signal (white), a reverse PWM signal (green) and forward PWM signal (red). These signals are all passed to the H-bridges from the control module via the router board.

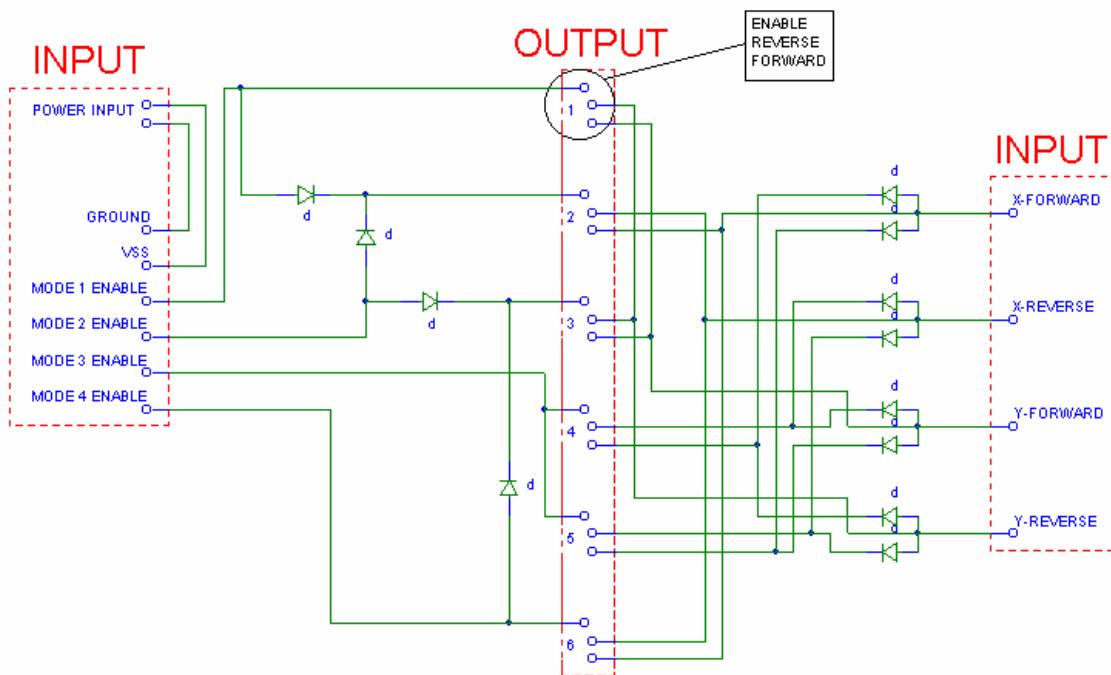


Figure E.7 - Router Board Schematic

Both the router board and the H-bridges were made in a similar manner using perf-boards and a silver pen. A perf-board is a silicon board (like a standard PCB) with 0.1" spaced holes pre-drilled in it. Each hole has its own copper pad to which things can be soldered. To make a "PCB" this way, you simply solder your components in place and connect everything by drawing

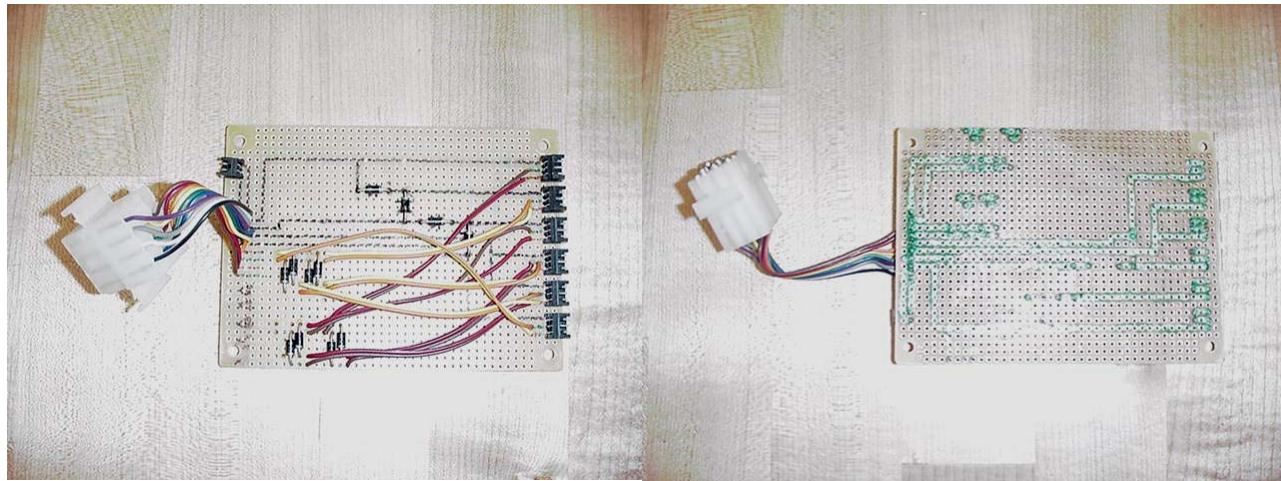


Figure E.8 - Router Board – Top (left), Router Board – Bottom (right)

traces with a conductive silver pen. To improve the physical durability of the otherwise delicate traces, you can cover them with a green overcoat pen or overcoat spray. In the case of the H-bridges, all of the large current-carrying connections were made with short pieces of 12 AWG wire rather than the traces to avoid burning up the traces.

The components on the H-bridge include: 2 p-channel MOSFETs, 3 n-channel MOSFETs, 2 NPN bipolar junction transistors (BJT), 9 1 k Ω resistors, 4 PCB mount male spade connectors and one 3-pin receptacle. Note that all of the part numbers are listed on the H-bridge schematic in the figure 11.10 below. Starting from the bottom of the H-bridge-top image, the spade connectors go as follows: ground, voltage supply, forward out to motor, reverse out to motor. The 3-pin input will only plug in one direction and the color convention is the same as mentioned above for the H-bridge

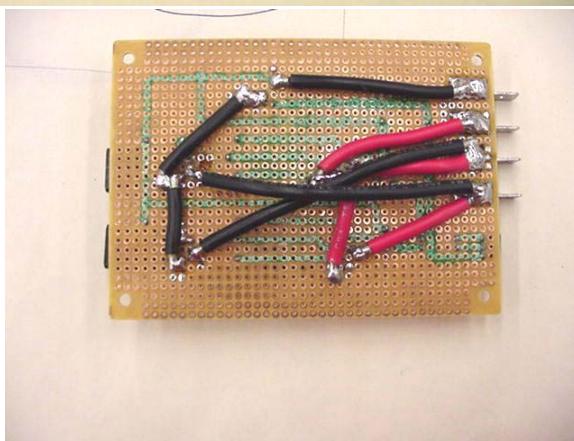
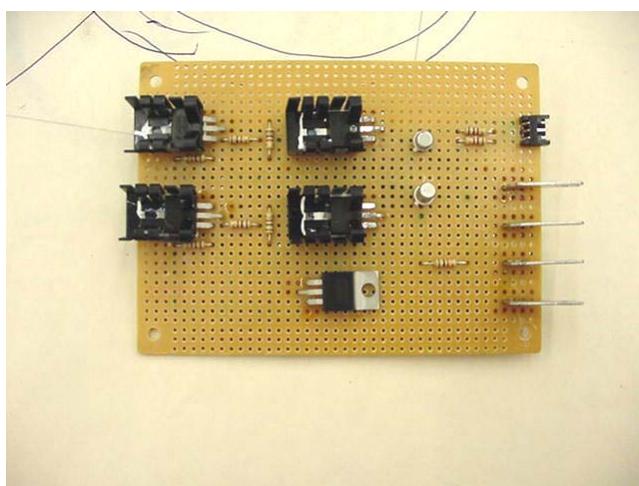


Figure E.9 - H-bridge-Top (above), H-bridge-Bottom (below)

outputs.

The H-bridge design is relatively standard with the exception of the enable transistor added just before the ground of the board (bottom-most transistor on the image). All of the H-bridges that are controlled by the same axis of the joystick receive input from the control module at the same time. The only way to limit activity to one H-bridge at a time is to provide a way to disable all of the others. This is done by the use of the mode enable lines from the control module along with the enable transistor found on each H-bridge. By sending a logic 0 (0 volts) to the enable transistor, the transistor is turned off, making the H-bridge an open circuit by disconnecting the ground. When a logic 1 is applied to the enable transistor (5 volts), the H-bridge becomes grounded and is, therefore, active. This is how the control system limits the motion to two motors at a time.

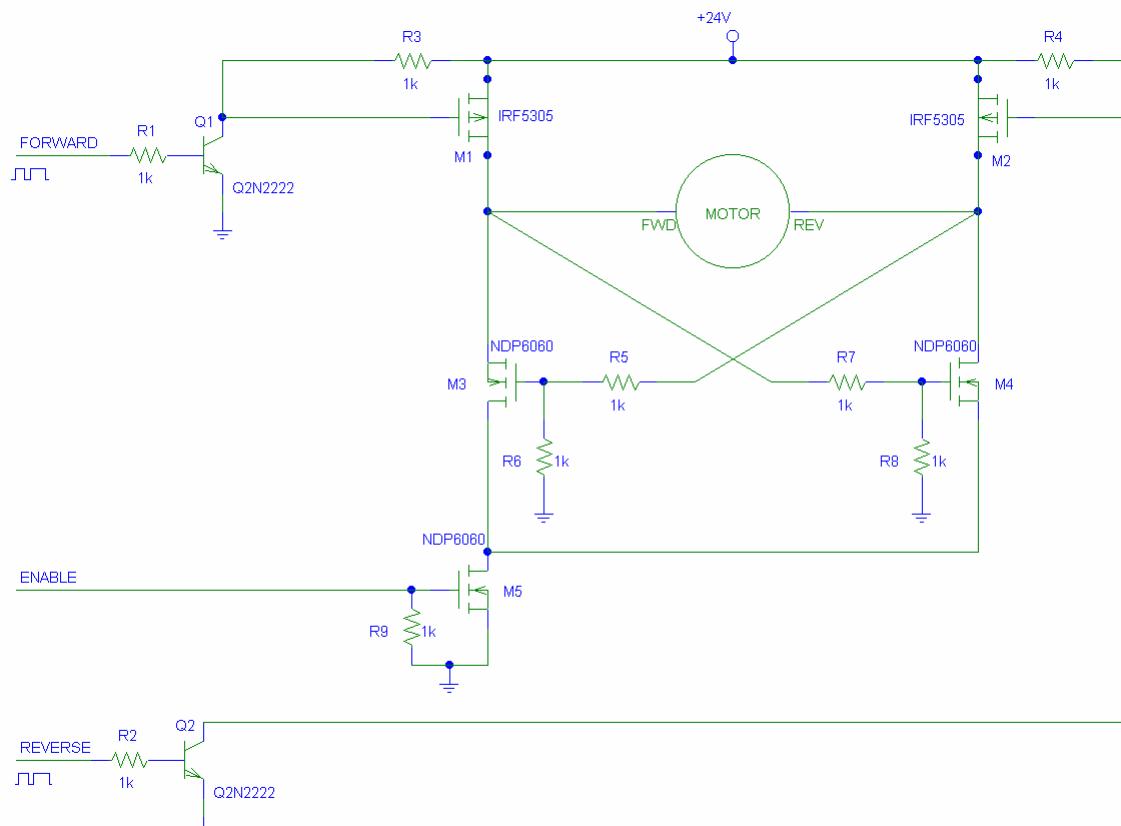


Figure E.10 - H-bridge Schematic

There are two motors that get both an x-axis signal pair and a y-axis signal pair. These are the wrist motors. Because of the differential system used in the wrist, both motors have to run together to move the wrist in either a twist or bend manner. For twist (x-axis), both motors

run in the same direction. For bend (y-axis), the motors run in opposite directions. To do this, the router board sends x- and y-axis signal pairs to both motors. However one of the motors receives a reversed y-axis signal pair. This corresponds to output set number 4 on the router board schematic and is also the same set on the actual board when looking at it from above.

Now, with all of these components, we have the makings of the amplifier module. Hook up a motor and a power supply, input the signals from the control module and we have a motor with variable speed. There is, however, one problem that can be devastating to the H-bridges. This problem occurs just before the motor starts moving. The problem is that when the motor is not turning it is not generating any back EMF and behaves like a simple piece of wire, a short circuit. This H-bridge design has no current limiting features. So, during motor startup, if the motor does not start to rotate immediately, there is a voltage drop of 24 volts across the three transistors in the active circuit path. All of these transistors have an operating resistance in the 10's of milli-ohm range meaning that the power they are dissipating is in the kilowatt region. The transistors cannot dissipate much power for more than a short time before they blow.

The simplest way to fix this problem is to put a low-value high-power resistor in series with the motor. In this case, the best resistance found on short notice was a 5Ω , 50W resistor and a 0.8Ω , 25W resistor. After PWM, the effective voltage across the motor is about 16V. That makes the power dissipation across the 5.8Ω resistance approximately 44W.

$$P = \frac{V^2}{R} = \frac{16^2}{5.8} \approx 44W$$

This may seem like a waste of power, but the only time this much power is dissipated by the resistors is before the motor starts moving. Once the motor starts to move – even a small

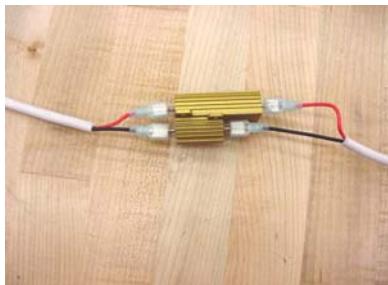


Figure E.11 - Resistor Block

amount – the motor's effective resistance (due to the back EMF) increases dramatically. So, the 5.8Ω is much less than the motor resistance and, therefore, most of the power is dissipated across the motor. The only real downside to the setup is that the effective current is limited to no more than about 2.75A. That's not strong enough to move the larger motors when they are loaded.

On a final note about amplification, there are several companies that make motor driver integrated circuits (ICs). One company in particular, Allegro Microsystems, makes the motor

driver IC 3952. This chip is a single-inline package (SIP) which has some nice features like current limiting, temperature protection, and dynamic breaking. One chip alone is only capable of delivering up to 2 A of current. However, these chips can be wired in parallel to deliver more current. For example, four chips in parallel would be able to deliver 8 A of current which is enough to drive the shoulder bend motor. Another plus is that an amplifier made of these chips would potentially be very small. Also, it is likely that it would only take some minor programming changes to the PICs in order to use these motor drivers with the current control module.

E.6 HARDWARE/CONSTRUCTION

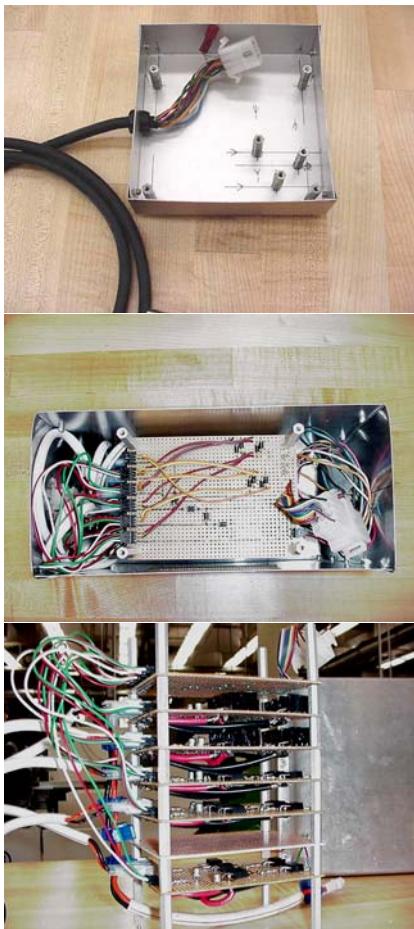


Figure E.12 - Control Box (top), Amplifier Box (middle), H-bridge Stack (bottom)

For this prototype design, it was decided to mount the modules in sheet metal boxes. Sheet metal boxes are inexpensive, easy to make, and easy to customize. In particular, sheet aluminum was used along with aluminum rivets.

To hold all of the boards in place inside their respective boxes, standoffs were used. These standoffs are hex-side (1/4") male/female threaded standoffs. For the control module, the standoffs were steel, 1/2" long and had 6-32 threading. There were fourteen in all: four on the top and bottom of each corner and another three on the top and bottom around the joystick to prevent the board from flexing and breaking when the joystick button is pushed. The amplifier module used 4-40 threaded, 3/4" long aluminum standoffs between the boards (24 standoffs in all) along with 8 4-40 threaded 1.5" aluminum standoffs on the top and bottom of the board stack. For both the control box and the amplifier box. The boards are attached to their respective boxes with nuts on the bottom and machine screws on the top which also holds the lid (4-40 threading for the amplifier box, 6-32 threading for the control box).

Inside the amplifier box, the main power connector is a 2-pin Molex plug (female) that enters through the back of the box (refer to Figure E.12). Inside there are two 12 AWG wires that run under the board stack and up the front with quick splice female spade connectors for five of the six H-bridges. The ends of the wires are topped off with right-angle female spade connectors to connect power to the top H-bridge. The connection to the motor from an H-bridge starts as two female spade connectors attached to two 16 AWG wires. On the other end of the wires is a 2-pin Molex plug (female) which sticks out through the front of the box. There are six in all. From the front of the box the power to the motor then goes through a resistor block and then on to the motor.

It's not important which H-bridges are hooked up to which motors because all of the bridges are the same. It is, however, very important that each motor's H-bridge be hooked up to the correct output from the router board depending on which degree of motion the motor is actuating. The following table is a list of the router board output number (found on the schematic of Figure E.7) and the corresponding motor it must be connected to. Remember that the actual router outputs physically correspond to those in the schematic when looking at the router from the top.

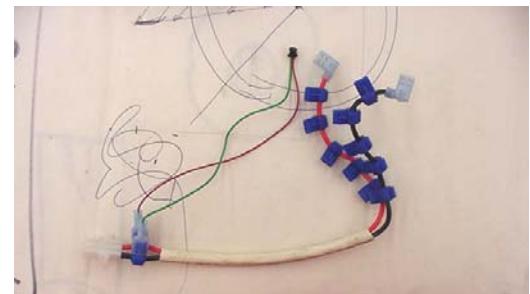


Figure E.13 - Amplifier Box Internal Power Connector

Table E.2 Router Board Output Hookup

ROUTER BOARD OUTPUT NUMBER	JOINT MOTION/MOTOR
1	Shoulder Bend
2	Shoulder Twist
3	Elbow Bend
4	Wrist Motor 1 (y-axis reversed)
5	Wrist Motor 2
6	Gripper Open/Close

A final bit of information that might be useful pertains to the making of the control module printed circuit board. Mostly all PCBs are created using the same general process. You start with a board completely plated with copper on one or both sides. You mask the copper you

want to keep using some form of etch-resistant covering. Finally, you etch the board using a chemical that dissolves the unmasked copper away. The most common chemicals used are ferric chloride and sodium perchlorate. The most significant difference between board making techniques lies in the way the board is masked.

A common form of masking (especially in industry), is the use of a photo-sensitive board. For this process, a negative of the circuit design is created and then, in a darkroom, the board is flashed with the image, exposing all of the parts that are to be masked. The exposed parts turn black and the rest is cleaned off. This process is very fast and precise, but requires a lot of equipment and chemicals.

Another means of masking is the use of an etch-resistant pen and/or etch-resistant decals. Both of these masking tools are good for quick and dirty PCB creation, but it is nearly impossible to make anything with any amount of precision or detail. The lack of precision makes this method practically worthless when the circuit contains items such as microchips that have pins that are very close together (0.1" spacing).

Another rather interesting masking technique, the one used to make the control board, is the use of toner transfer paper. This paper, when printed on or photocopied on with some sort of a toner-based printing system (such as a laser printer) can be ironed onto the copper-clad board just like an iron-on transfer for a t-shirt. The board and paper are then put into water to dissolve the adhesive that holds the toner to the paper (just like a decal). The board is then etched and drilled.

E.7 CODE

The following code was use for the alternative controls system. This code is to be used with the Microchip Inc. PIC16F84 only. The code is for both PICs used in the alternative controls system.

E.7.1 HEADER FILE

```
; ; 16F84REG.INC: PIC 16F84 Registers

ifndef __16C84REG_INC__

__16F84REG_INC__ equ 1

;; SPECIAL REGISTERS
INDF equ 0x00
TMRO equ 0x01
PCL equ 0x02
STATUS equ 0x03
FSR equ 0x04
PORTA equ 0x05
PORTB equ 0x06
EEDATA equ 0x08
EEADR equ 0x09
PCLATH equ 0Ah
INTCON equ 0Bh

OPTION_REG equ 81h
TRISA equ 85h
TRISB equ 86h
EECON1 equ 88h
EECON2 equ 89h

RAM_BASE equ 0ch

;; STATUS REGISTER
;; =====
C equ 0
DC equ 1
Z equ 2
PD equ 3
T0 equ 4
RP0 equ 5
RP1 equ 6
IRP equ 7

;; PORTA Bits
;; =====
RA0 equ 0
RA1 equ 1
```

```

RA2    equ    2
RA3    equ    3
RA4    equ    4
TOCKI equ    4

;; PORTB Bits
;; =====
RB0    equ    0
INT    equ    0
RB1    equ    1
RB2    equ    2
RB3    equ    3
RB4    equ    4
RB5    equ    5
RB6    equ    6
RB7    equ    7

;; INTCON REGISTER
;; =====
RBIF   equ    0
INTF   equ    1
TOIF   equ    2
RBIE   equ    3
INTE   equ    4
TOIE   equ    5
EEIE   equ    6
GIE    equ    7

;; OPTION REGISTER
;; =====
PS0    equ    0
PS1    equ    1
PS2    equ    2
PSA    equ    3
TOS1E  equ    4
TOCS   equ    5
INTEDG  equ    6
RBPU   equ    7

;; EECON1 REGISTER
;; =====
RD     equ    0
WR     equ    1
WREN  equ    2
WRERR equ    3
EIF    equ    4

;; destination bits
w      equ    0
f      equ    1

;; SPECIAL PROGRAM ADDRESSES

```

```

PROGRAM_START      equ    0
INTERRUPT_START   equ    4

;; CONFIGURATION FUSE
;; D1,0: FOSC1, FOSCO
LPOSC equ    0
XTOSC equ    1
HSOSC equ    2
RCOSC equ    3
;; D2: Watchdog timer enable
WDTENABLED equ    4
;; D3: Power up timer disable
PWRUPTMRDISABLED equ    8
;; D4: Code protection disable
CODEPROTDISABLE equ    16

        endif
;; end of 16F84REG.INC

```

E.7.2 MAIN PROGRAM

```

; FILE:      control1.asm
; DESC:      This program has two functions. The first is to provide a
variable
;      speed motor control via pulse width modulation based on an 8-bit
;      digital conversion of an analog voltage from a potentiometer. Note
;      that the conversion is done externally by an analog-to-digital
converter
;      (National Semiconductor's ADC0831CCN). The other function of this
;      is to provide the ability to select the active joint on the arm. The
;      joint is selected by pressing a button connected to bit 7 of Port B.
;      The joint selection is cycled with each press until the desired joint
is
;      activated. Note that no motor on the arm will function while the
button
;      is depressed.
;
; DATE:      04.08.2001
; VER:       1.0 (04.26.2001)

list p=16F84
radix hex

__config 0x3ff2      ; PWRT on, WDT off, HS oscillator, no code
protection

; Set up custom file registers
input equ 0x0c
ontime equ 0x0d
offtime equ 0x0e

```

```

w_tmp equ 0x0f
stat_tmp equ 0x10
joint equ 0x11

#include <16F84reg.inc>

org 0x000
goto init

; Interrupt Handler_____
org 0x004
movwf w_tmp ; ~|
movf STATUS,w ; | - Save current state
movwf stat_tmp ; _|
btfsC INTCON,RBIF ; Check for joint select
goto btn_intr

; This simply counts down the PWM on-time
on_intr movf ontime,w ; ~|- if ontime > 0
        iorlw d'0' ; | ontime = ontime - 1
        btfsC STATUS,Z ; | restore state
        goto off_intr1 ; | return
        decf ontime,f ; | else
        call restore ; _| goto off_intr1
        retfie ; _| 

; These count down PWM off-time, but at certain points
; other tasks are performed
off_intr1 movlw d'20' ; ~|- if offtime > 20
        subwf offtime,w ; | offtime = offtime - 1
        btfsS STATUS,C ; | restore state
        goto off_intr2 ; | return
        decf offtime,f ; | else
        call restore ; _| goto off_intr2
        retfie ; _| 

; During this segment of off-time, the ADC is prepared
; for outputting the serial signal
off_intr2 movlw d'16' ; ~|- if offtime > 16
        subwf offtime,w ; | cycle ADC CLK 1/2 clock
        btfsS STATUS,C ; | offtime = offtime - 1
        goto off_intr3 ; | restore state
        movlw b'00000010' ; | return
        xorwf PORTB,f ; | else
        decf offtime,f ; | goto off_intr3
        call restore ; _|
        retfie ; _| 

; For this segment of off-time, the bits are read
; from the ADC and stored to "input". Because only

```

```

; one bit is read for every timer interrupt (every
; 256 clock cycles), the process is slow enough for
; the ADC to create nice, stable output
off_intr3    movlw d'8'           ; ~|- if offtime > 8
              subwf offtime,w      ; | call bit_read (read/store one bit from
ADC)          btfss STATUS,C       ; | offtime = offtime - 1
              goto off_intr4        ; | restore state
              call bit_read          ; | return
              decf offtime,f         ; | else
              call restore            ; | goto off_intr4
              retfie                 ; _|
              ; This section simply counts down all of the
              ; remaining off-time
off_intr4    movf offtime,w      ; ~|- if offtime > 0
              iorlw d'0'             ; | offtime = offtime - 1
              btfss STATUS,Z          ; | restore state
              decf offtime,f         ; | return
              call restore            ; |
              retfie                 ; _|
              ; This is the algorithm that handles the joint
              ; selection procedure
btn_intr     clrf PORTA          ; Turn off all joints
              bcf  PORTB,4            ; ~|
              bcf  PORTB,5            ; |- Turn off/reset PWM signal
              clrf ontime             ; |
              clrf offtime             ; _|
              incf joint,f            ; ~|
              movf joint,w            ; |
              xorlw d'4'              ; |- Determine next joint to be
              btfsc STATUS,Z          ; | selected
              clrf joint               ; _|
lo?          btfsc PORTB,7          ; ~|- Loop until button is released
              goto lo?                ; _|
              movf joint,w            ; ~|
              call joint_tbl          ; |- Select the next joint
              movwf PORTA              ; _|
              call restore             ; Restore state
              retfie                  ; Return
              ; This is used to restore the state of the STATUS register
              ; and the "Working" (w) register because the main program
              ; may have been in the middle of using them for something
              ; when the interrupt occurred.
restore      movf stat_tmp,w
              movwf STATUS
              movf w_tmp,w
              bcf  INTCON,TOIF
              bcf  INTCON,RBIF
              return

```

; Initialization

```
; Chip configuration, set initial values
init bsf STATUS,RPO
    movlw b'10001100' ; ~|- Teach Port B (bits 2, 3, 7 input; all others
output)
    movwf TRISSB      ; _|
    movlw 0x00          ; ~|- Teach Port A (all bits output)
    movwf TRISA        ; _|
    movlw b'00001000' ; ~|- 1:1 Pre-scaler for TMRO
    movwf OPTION_REG   ; _|
    movlw b'10100000' ; ~|- Global Intr On, TMRO Intr On, RB Intr On
    movwf INTCON       ; _|
    bcf STATUS,RPO
    bcf INTCON,7       ; Temporarily disable interrupts
    clrf PORTA
    clrf PORTB
    movlw d'127'        ; ~|- Start with first input at the "center"
    movwf input         ; _|
    clrf joint
    bsf PORTA,0         ; Activate Joint 0 (see data table for name)
    bsf INTCON,7         ; Re-enable interrupts
```

; Main Program Body

```
main bsf PORTB,0           ; Clear/Reset ADC
    movf input,w          ; ~|
    sublw d'100'            ; |- if input < 100, goto rev
    btfsc STATUS,C          ; |
    goto rev                ; _|
    movf input,w          ; ~|
    sublw d'155'            ; |- if input >= 155, goto fwd
    btfss STATUS,C          ; |
    goto fwd                ; _|
    clrf ontime             ; --- else ontime = 0
    ; Do this stuff while the PWM signal is on
on_loop    movf ontime,w        ; ~|
    iorlw d'0'              ; |- Loop until ontime runs out
    btfss STATUS,Z          ; |
    goto on_loop             ; _|
    bcf PORTB,4              ; ~|- Turn off PWM signal
    bcf PORTB,5              ; _|
    bcf PORTB,1              ; ADC CLK Low
    bcf PORTB,0              ; Tell ADC to start conversion process
    movlw d'50'              ; ~|- offtime = 50
    movwf offtime            ; _|
```

; Do this stuff while the PWM signal is off

```
off_loop   movf offtime,w        ; ~|
    iorlw d'0'              ; |- Loop until offtime runs out
    btfss STATUS,Z          ; |
```

```

goto off_loop           ; _|
goto main
; Do this to make motor run in forward direction
fwd movlw d'145'          ; ~|
subwf input,w           ; |- ontime = input - 145
movwf ontime            ; _| NOTE: 11 <= ontime <= 111
bsf PORTB,5             ; Turn on forward PWM signal
goto on_loop
; Do this to make motor run it reverse direction
rev movf input,w          ; ~|
sublw d'110'             ; |- ontime = 110 - input
movwf ontime            ; _| NOTE: 11 <= ontime <= 111
bsf PORTB,4             ; Turn on reverse PWM signal
goto on_loop
; Read in one bit of data from ADC
bit_read   bsf PORTB,1      ; ADC CLK High (ADC clock signal high)
bcf STATUS,C             ; ~|
btfsC PORTB,2             ; |- Carry Bit = bit read from ADC
bsf STATUS,C             ; _|
rlf input,f              ; Rotate read bit into input
bcf PORTB,1               ; ADC CLK Low
return
; Joint selection data table
joint_tbl addwf PCL,f
retlw b'00000001' ; Activate Shoulder    (Joint 0)
retlw b'00000010' ; Activate Elbow     (Joint 1)
retlw b'00000100' ; Activate Wrist     (Joint 2)
retlw b'00001000' ; Activate Gripper   (Joint 3)
end

```

APPENDIX F

MOTOR TESTING PROCEDURE

The motor testing procedure requires the following equipment:

- ◆ Magtrol Dynamometer Model HD-710-8
- ◆ Magtrol Model 5210 Power Supply
- ◆ Magtrol Model Number BL-001 Cooling Fan
- ◆ 5V DC Power Supply
- ◆ 22V DC Power Supply
- ◆ Oscilloscope
- ◆ Voltmeters (2)
- ◆ Ammeter

Purpose: Establish a lab procedure to obtain necessary data from certain motors in order to plot a torque versus speed curve.

Procedure:

- 1) Obtain motor.
- 2) Connect necessary output wires to motor. These wires may be used to collect data from the motor such as voltage and current draw.
- 3) Place motor on test stand. For this step, a test stand may need to be fabricated specifically for the motor being tested.
- 4) Connect motor to brake via a shaft. (Brake should be attached to Magtrol Dynamometer Model HD-710-8.)
- 5) Supply 5V DC to the encoder. (See Magtrol Dynamometers manual for details.)
- 6) Supply 22V DC to the torque output. (See Magtrol Dynamometers user's manual for details.)
- 7) **Turn on cooling fan** (Magtrol Model Number BL-001). Caution must be taken while performing the test. Brake may overheat and cause permanent damage. (See Magtrol Dynamometers user's manual for horsepower versus time curves for maximum allowed testing times.)
- 8) Turn on brake current supply (Magtrol Model 5210 Power Supply). This is used to vary the torque applied by the brake.
- 9) With motor running, raise current being supplied to the brake slowly until the torque level reaches the stall torque of the brake. Record this value.
- 10) Connect oscilloscope to encoder output. (See Magtrol Dynamometers user's manual for details.) This frequency observed corresponds to the speed of the motor.
- 11) Connect voltmeter to torque output. (See Magtrol Dynamometers user's manual for details.) The voltage observed corresponds to the torque (100 mV = 1 N-m).

- 12) Connect voltmeter to voltage output on motor.
- 13) Connect ammeter to current output on motor.
- 14) Set brake current to value found in step 9.
- 15) Start motor.
- 16) Record necessary data.
- 17) Reduce brake current.
- 18) Record data.
- 19) Repeat steps 15 and 16 until brake current is zero.
- 20) Create plot using gathered data.

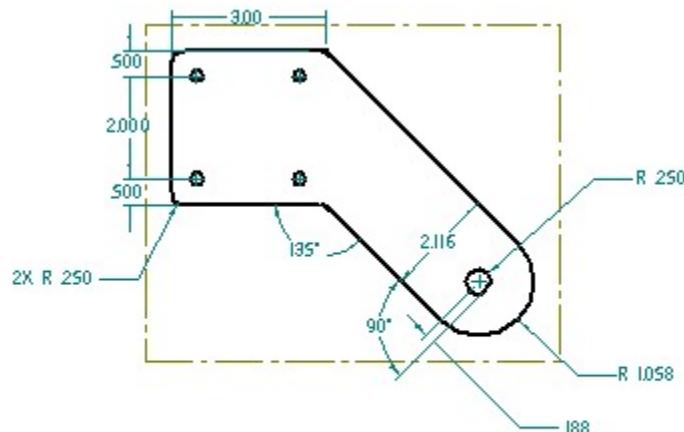
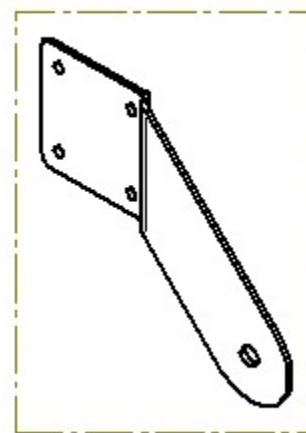
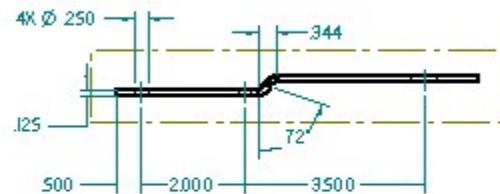
Data: The following table should be used to record data obtained from motor testing:

Table F.1 – Motor Testing Data Table

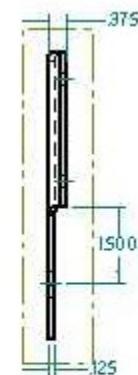
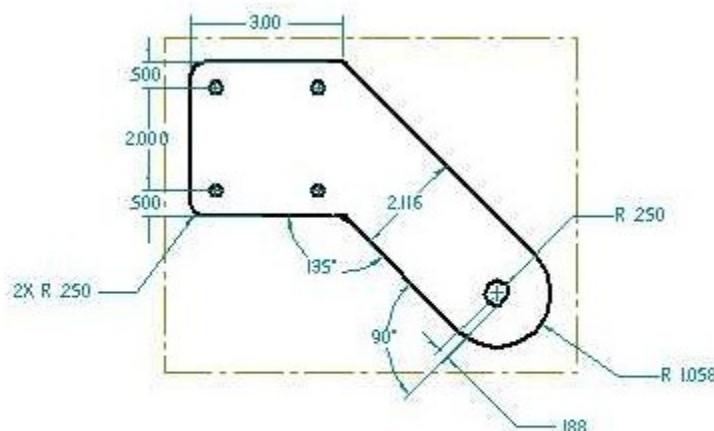
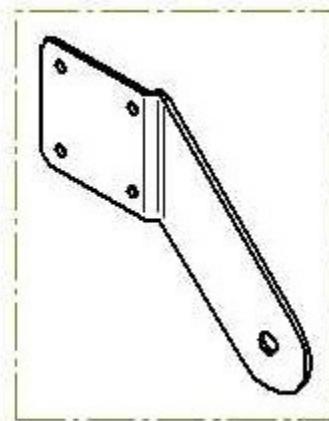
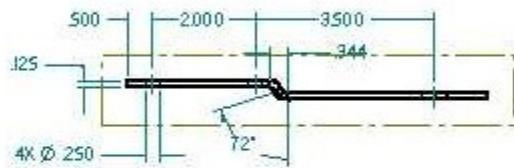
APPENDIX G

PART DRAWINGS

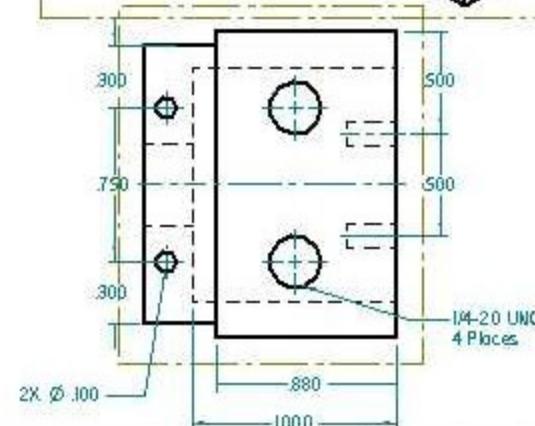
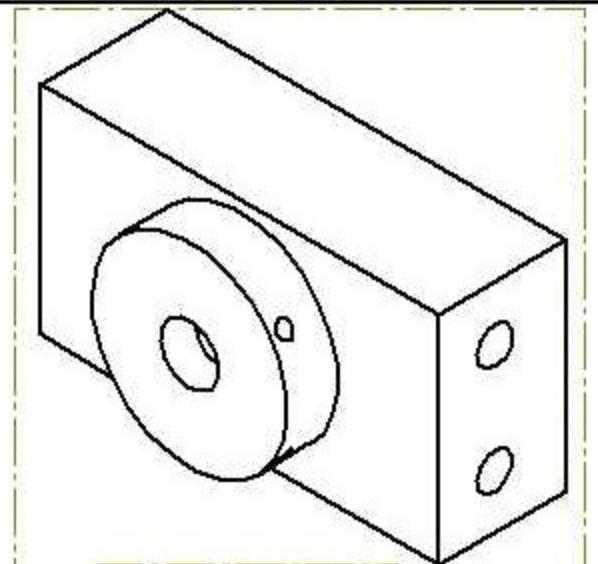
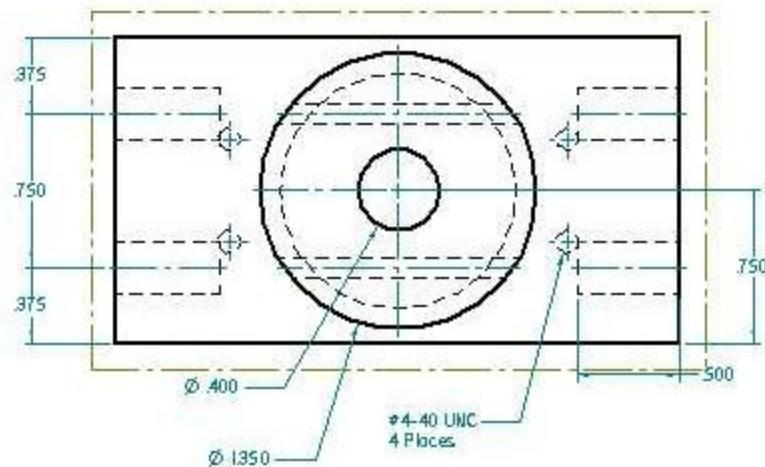
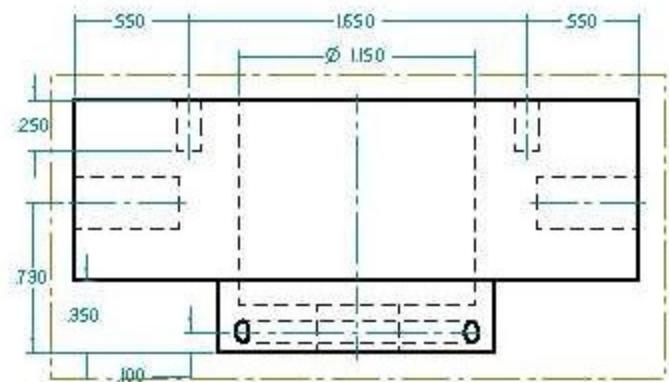
This section contains all of the two dimensional part drawings for the robotic manipulator.



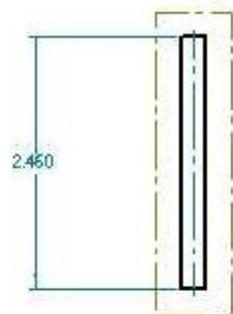
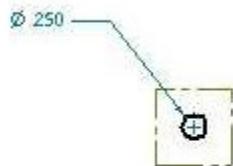
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ERIC YU				.12	INCHES	



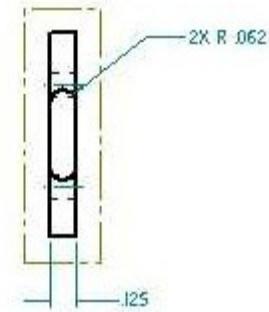
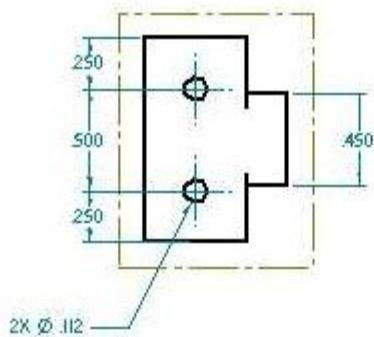
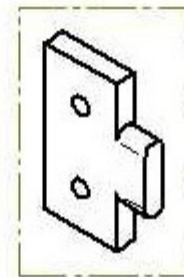
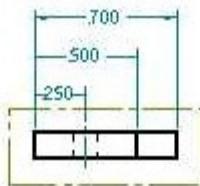
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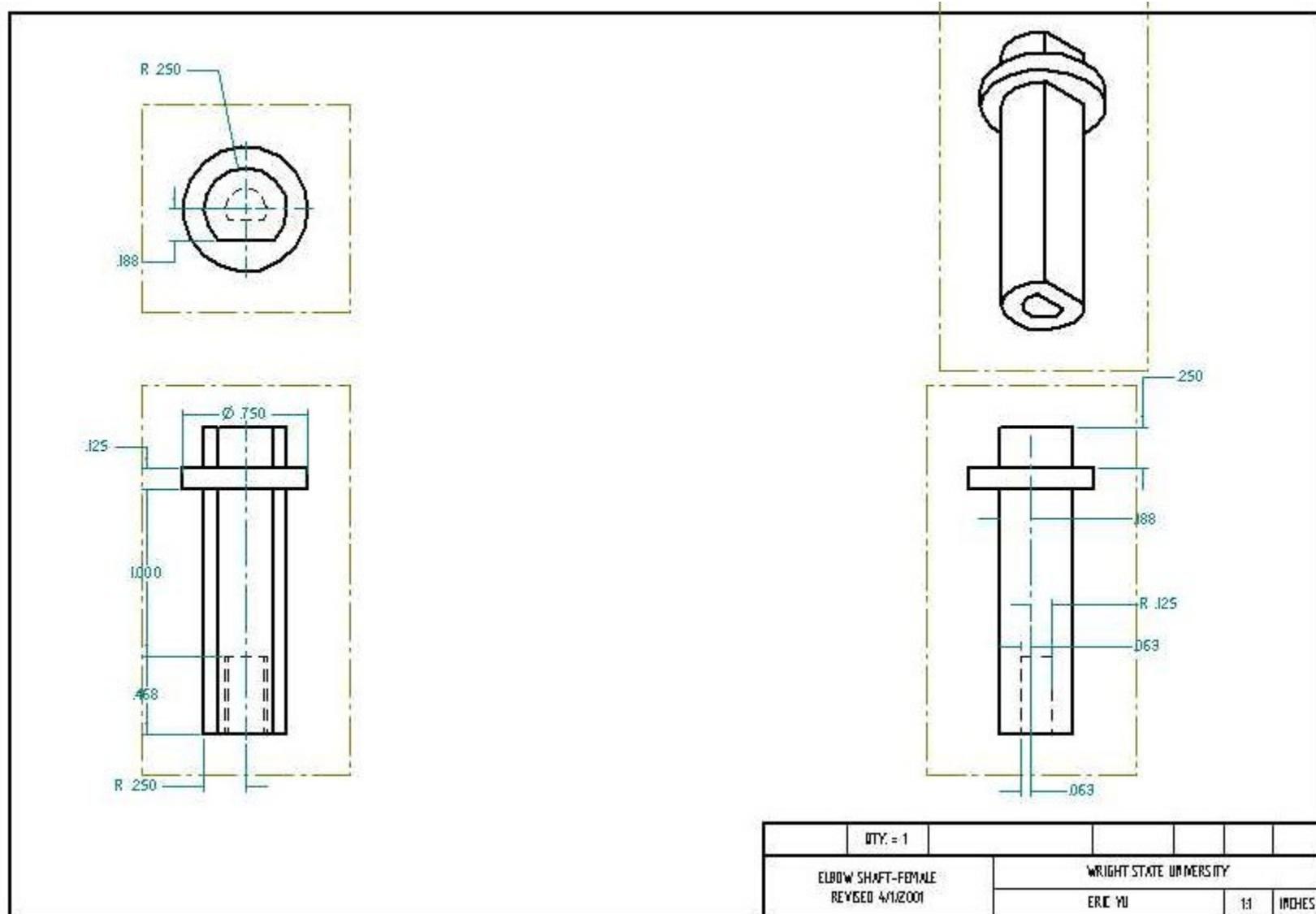
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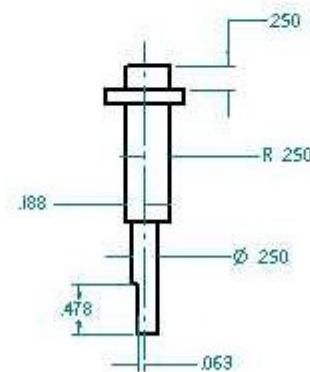
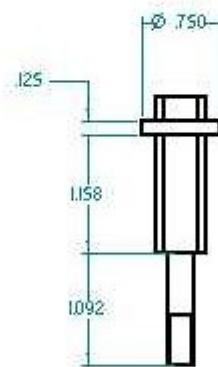
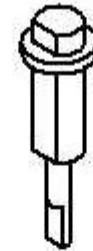
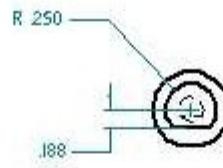


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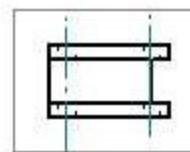
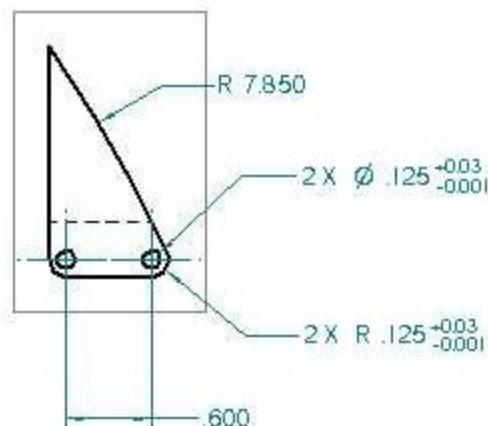
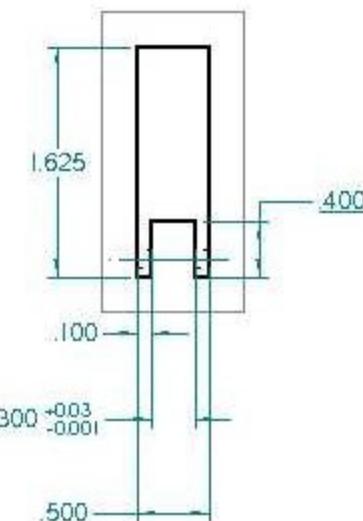
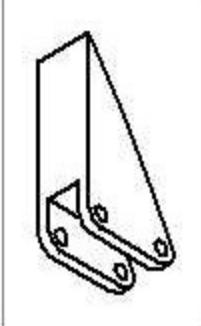


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ERIC YU		I:I		INCHES	





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ALTERNATIVE MALE ELBOW SHAFT REVISED: 4/16/2001				WRIGHT STATE UNIVERSITY ERIC YU I: INCHES			
						I:	INCHES



All Tolerances:
+ - 0.05 in
unless stated

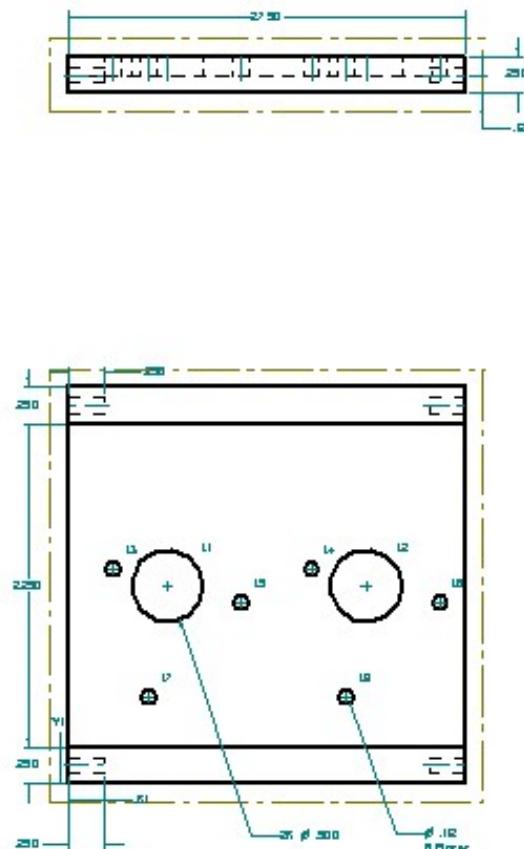
Ohio State University Gateway Coalition

Round Top Finger

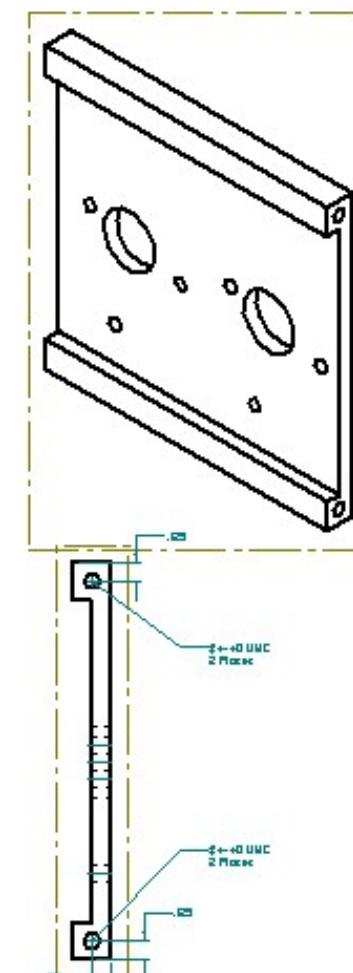
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M Hunt

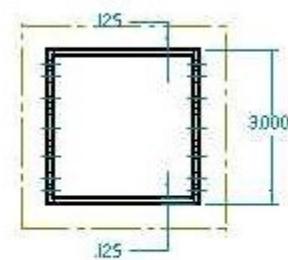
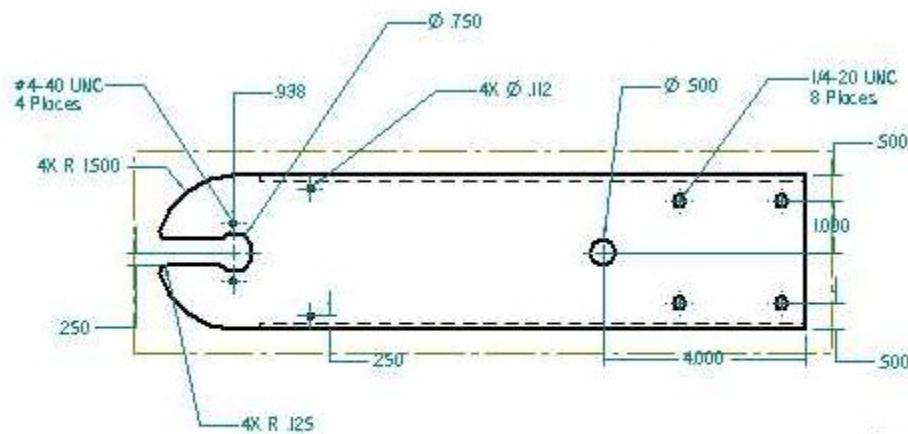
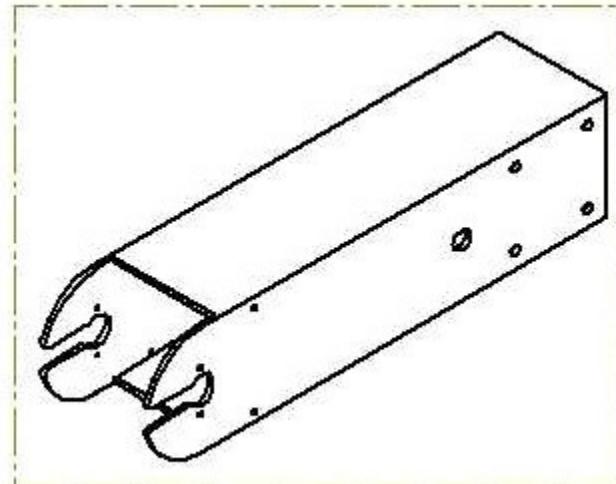
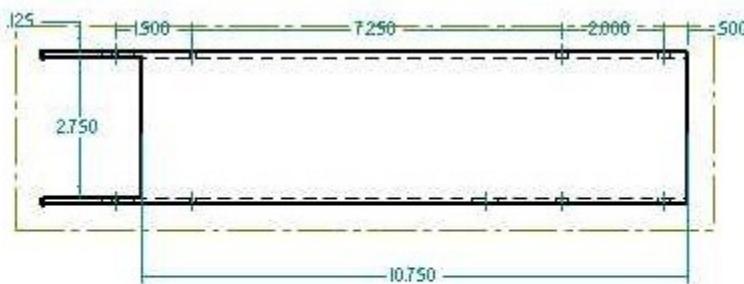
All Dimensions are Inches



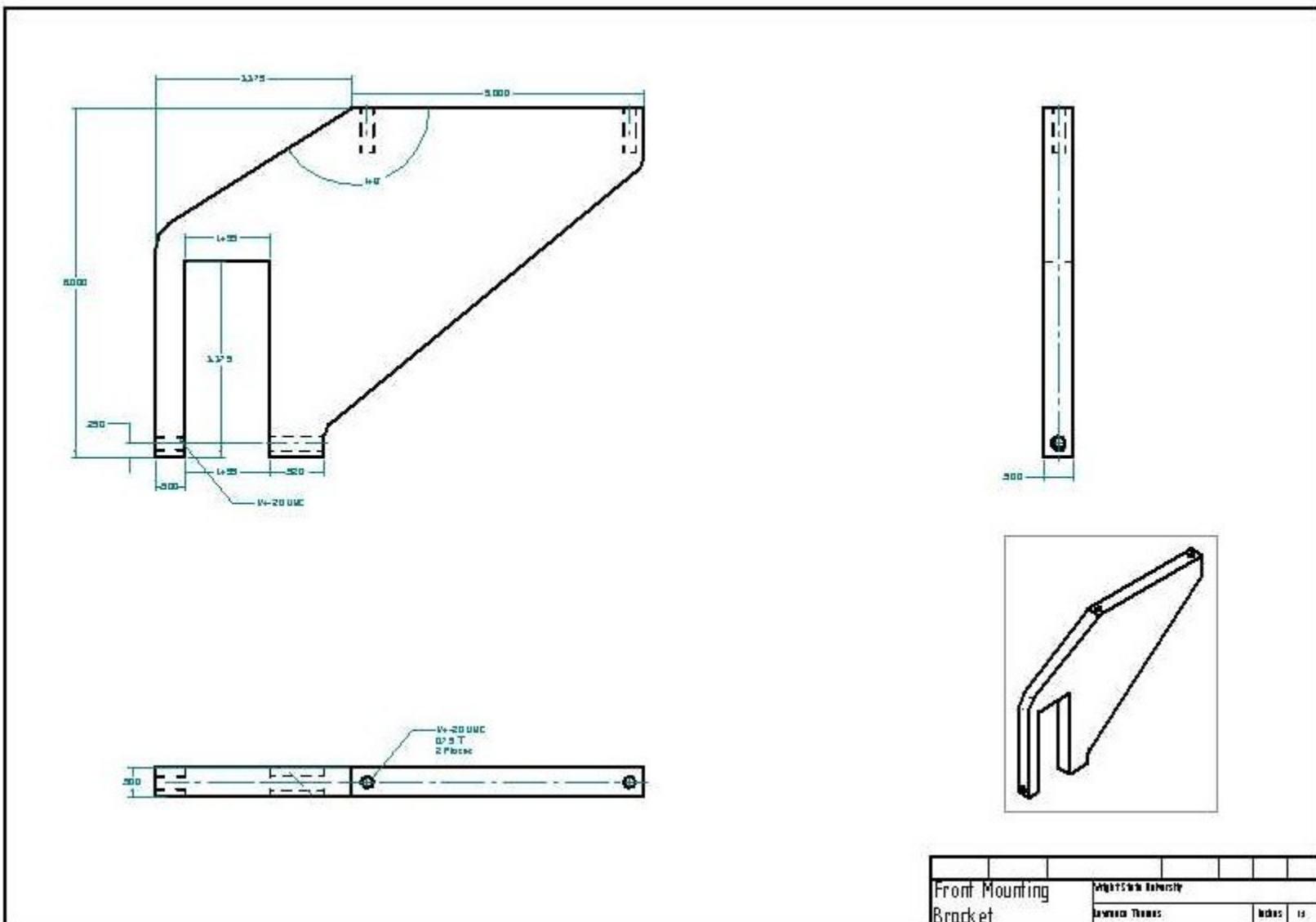
Hole Table		
Hole	X	Y
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L2	20.0	12.5
L3	30.0	14.0
L4	10.0	14.0
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L6	20.0	12.0
L7	20.0	10.0
L8	30.0	10.0



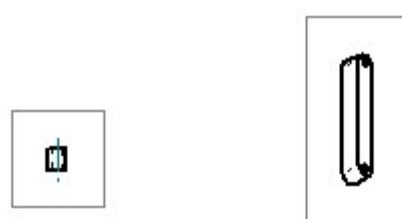
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	ERIC YU	EL	INCHES



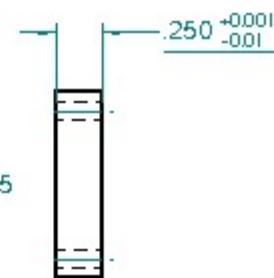
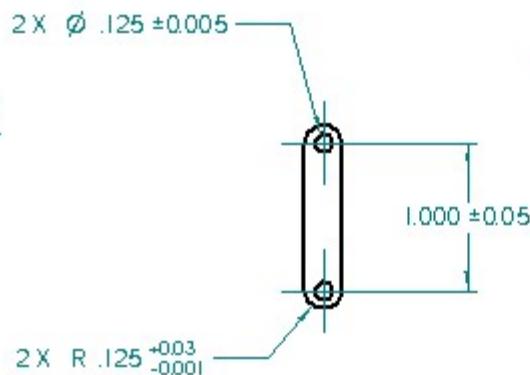
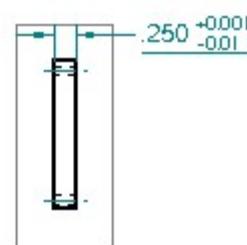
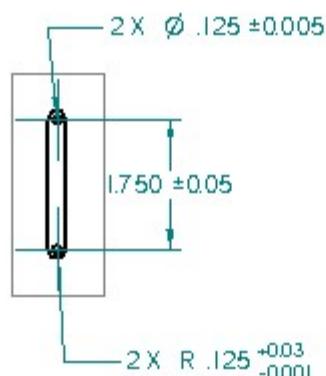
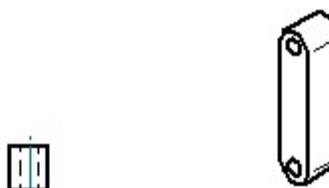
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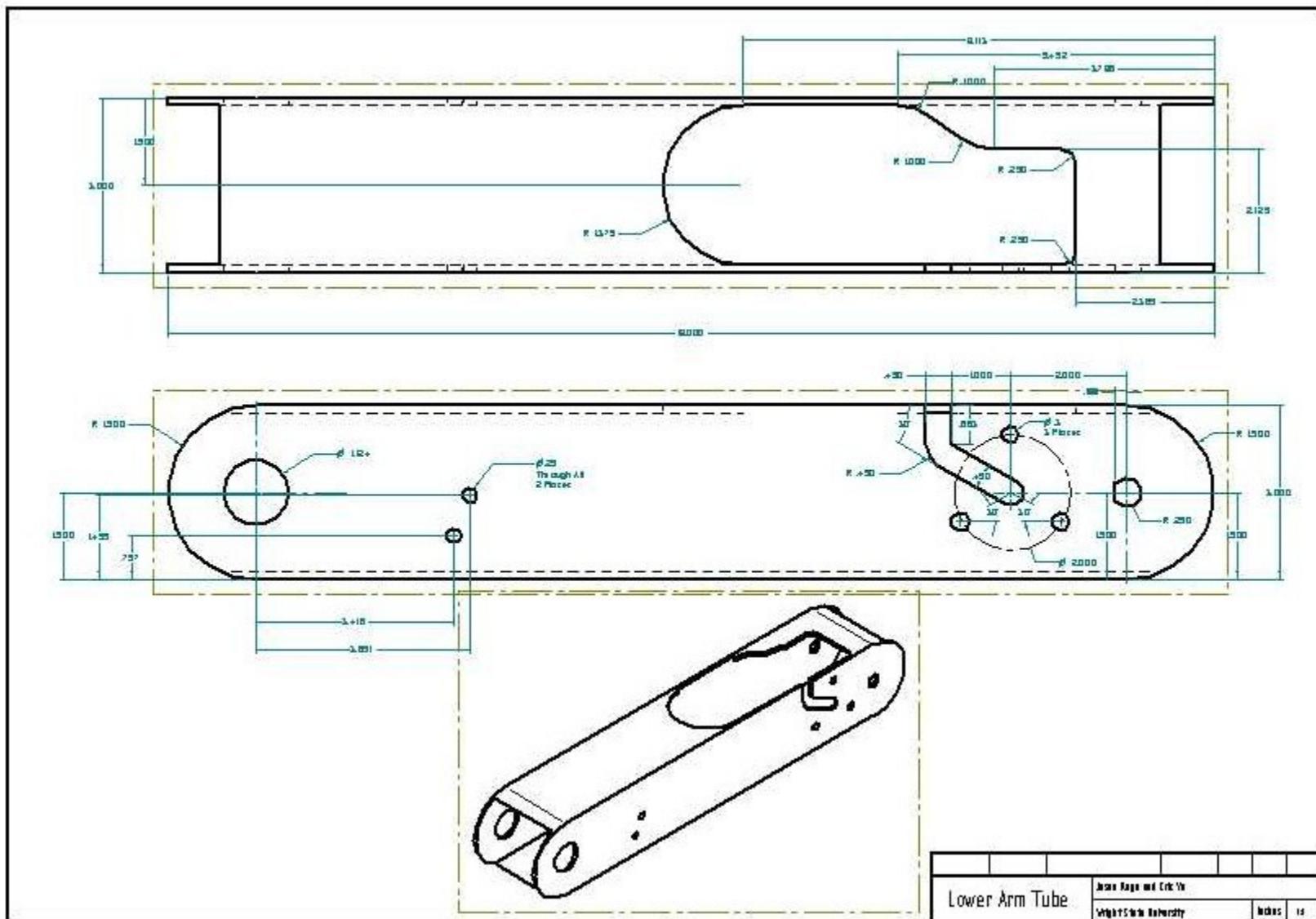
1.75' Link

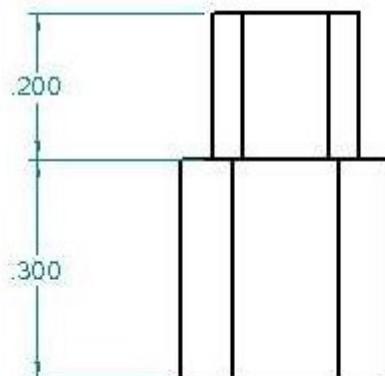
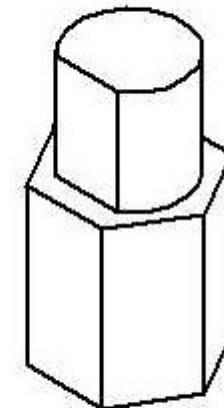
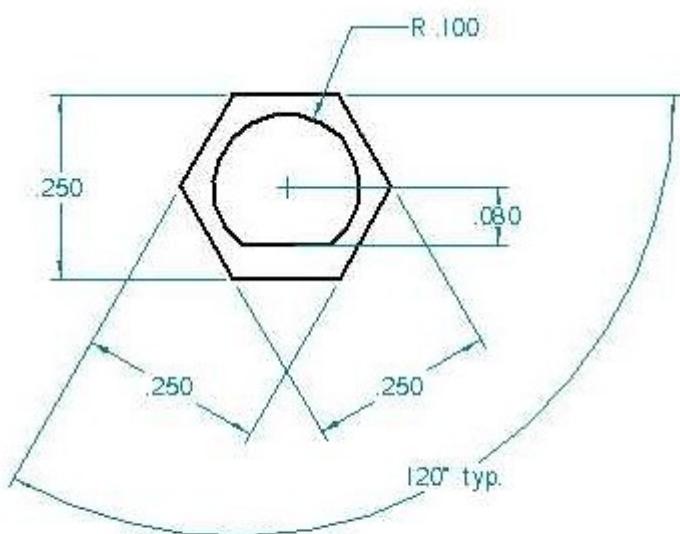


1.00' Link



	Ohio State University Gateway Coalition		
	1.75' Link & 1.00' Link		
		All Dimensions Inches	
Material: Aluminum	M Hunt	2-24-00	





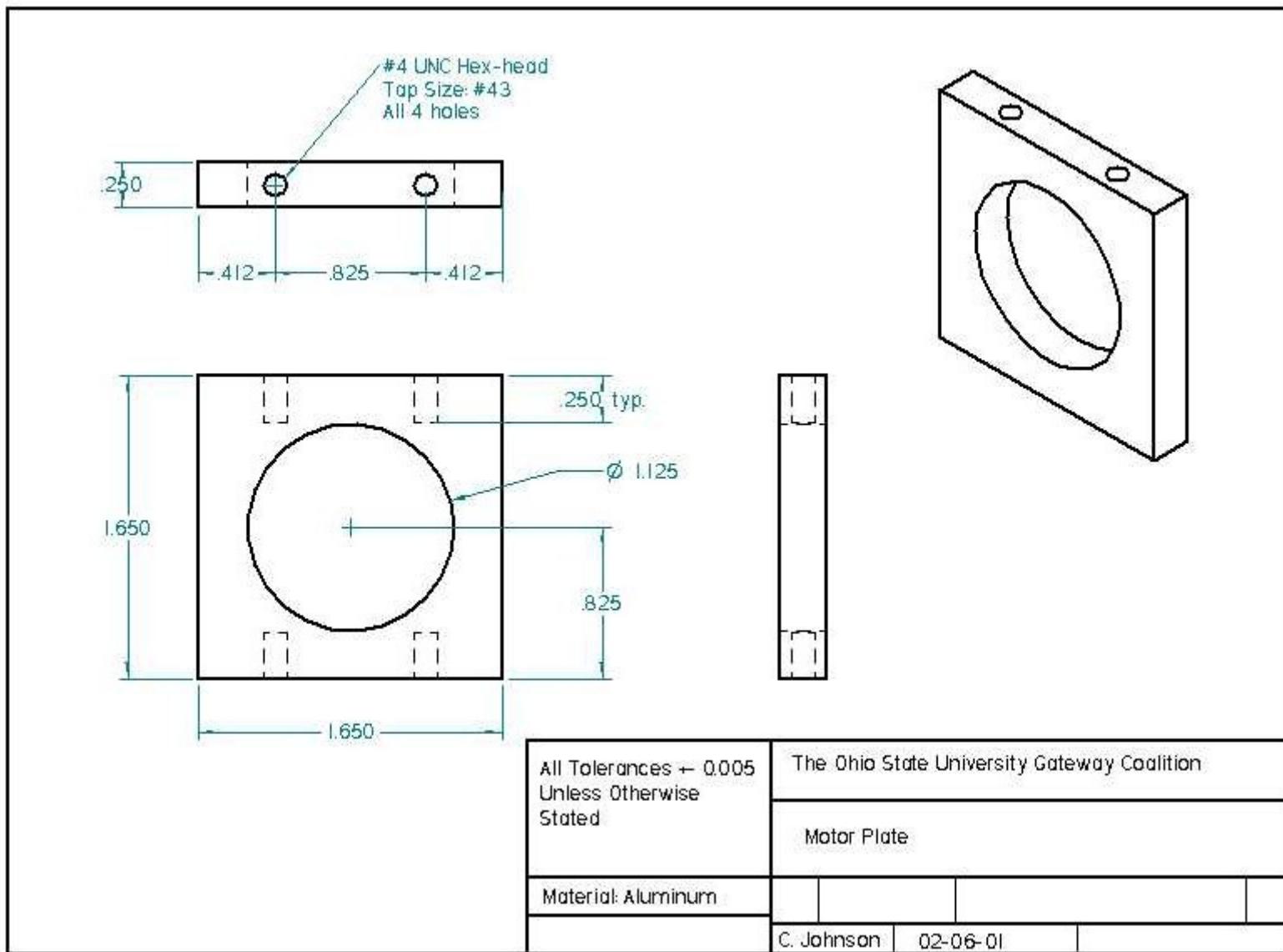
All Tolerances ± 0.005
Unless Otherwise
Stated

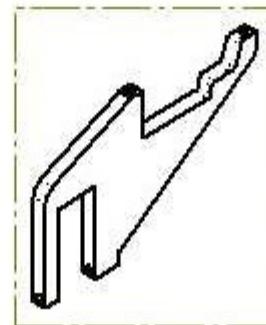
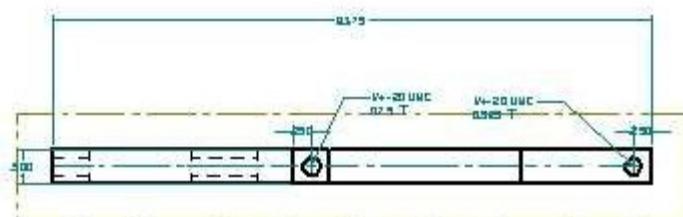
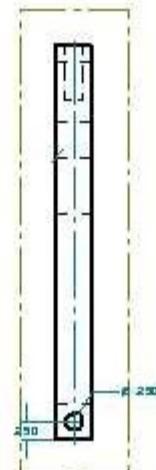
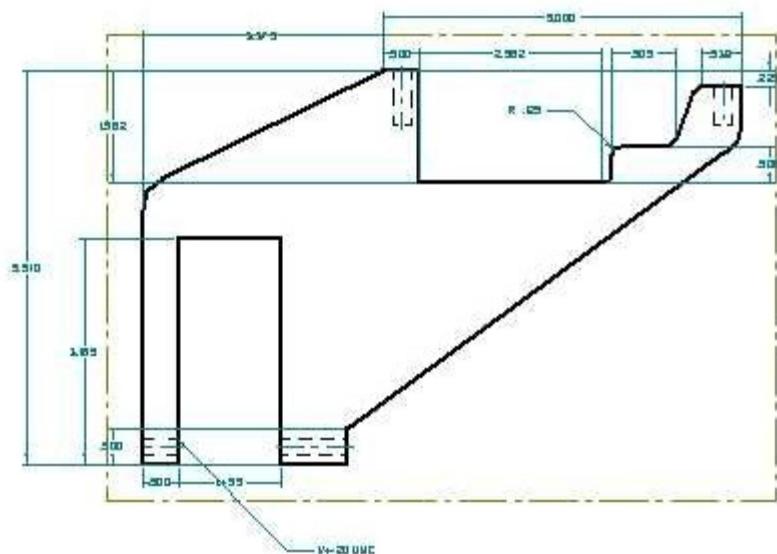
The Ohio State University Gateway Coalition

Motor Bit

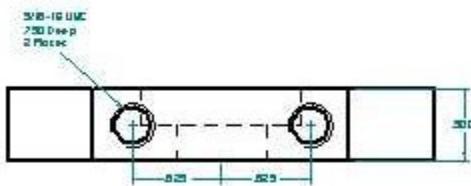
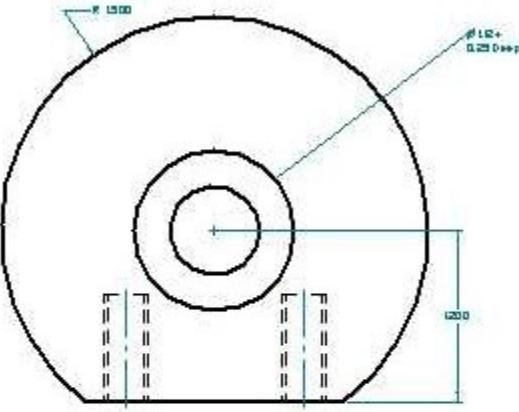
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C. Johnson 02-06-01

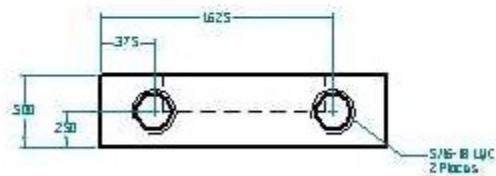
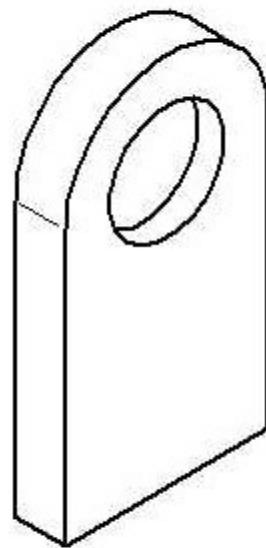
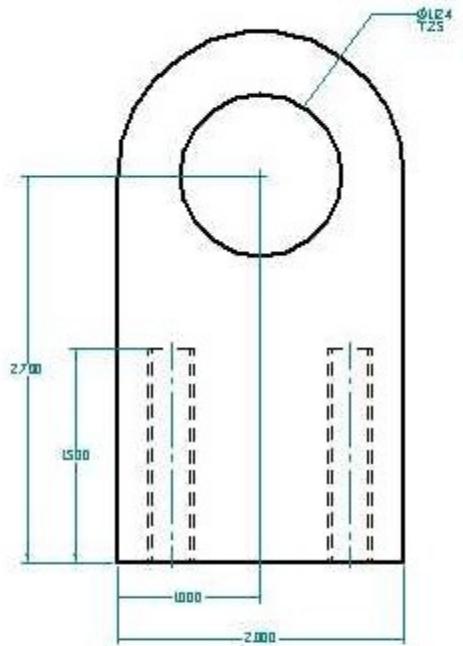




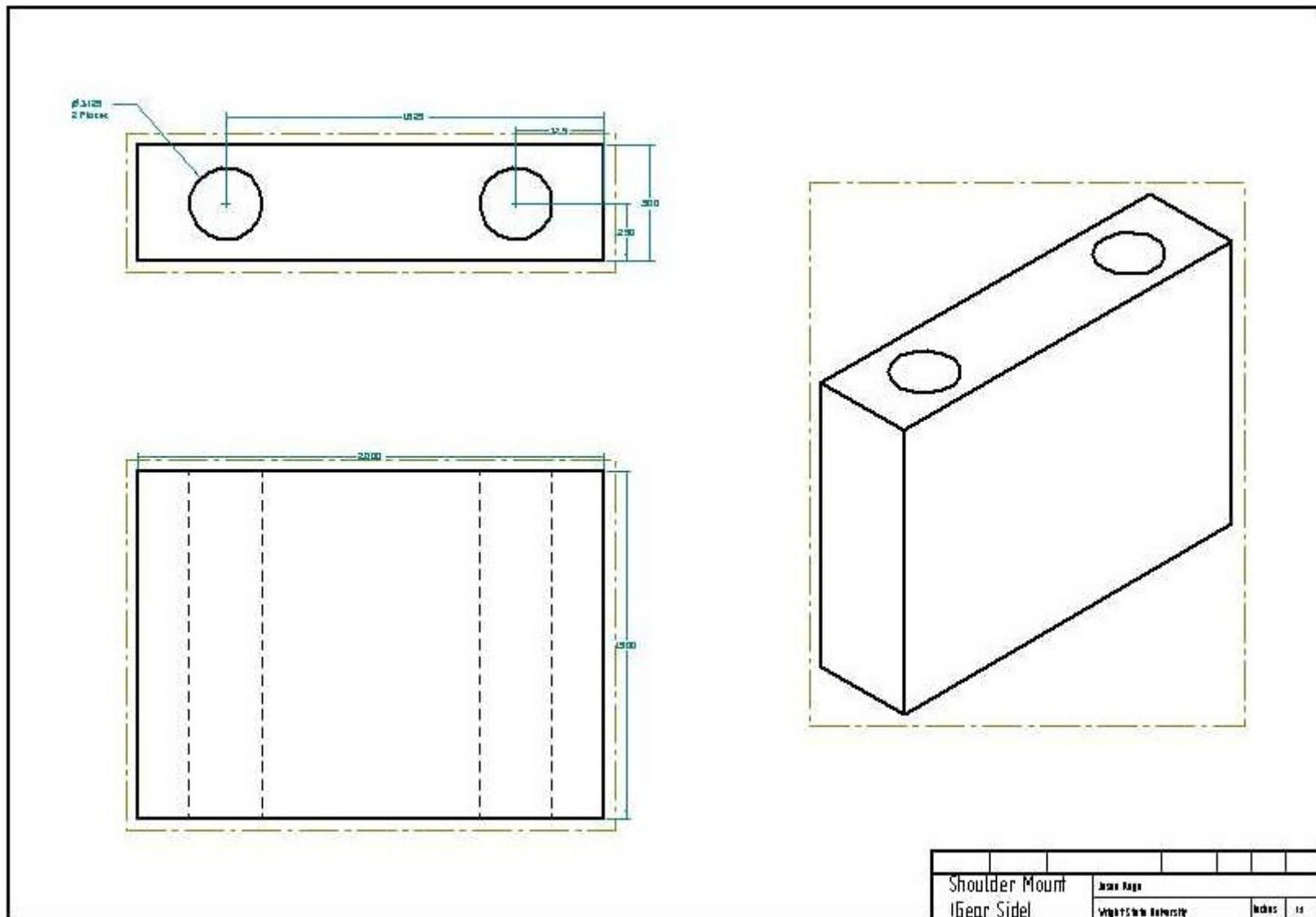
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		University Name	Value	Value	Value

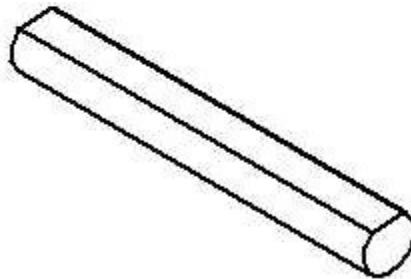
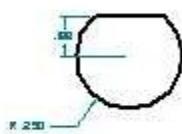


Shoulder Gear	Weight	State University
Jesse Raga	15	inches

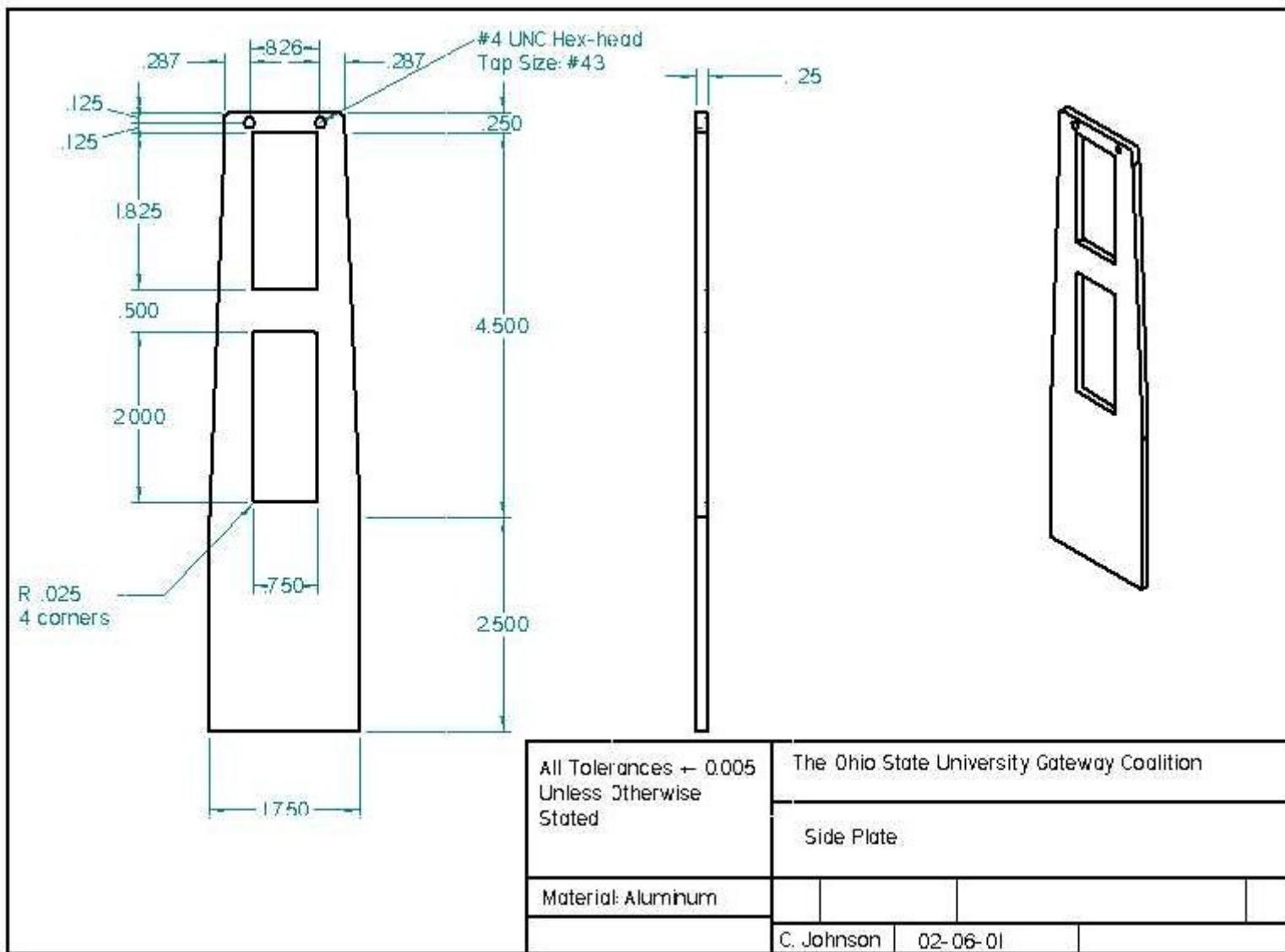


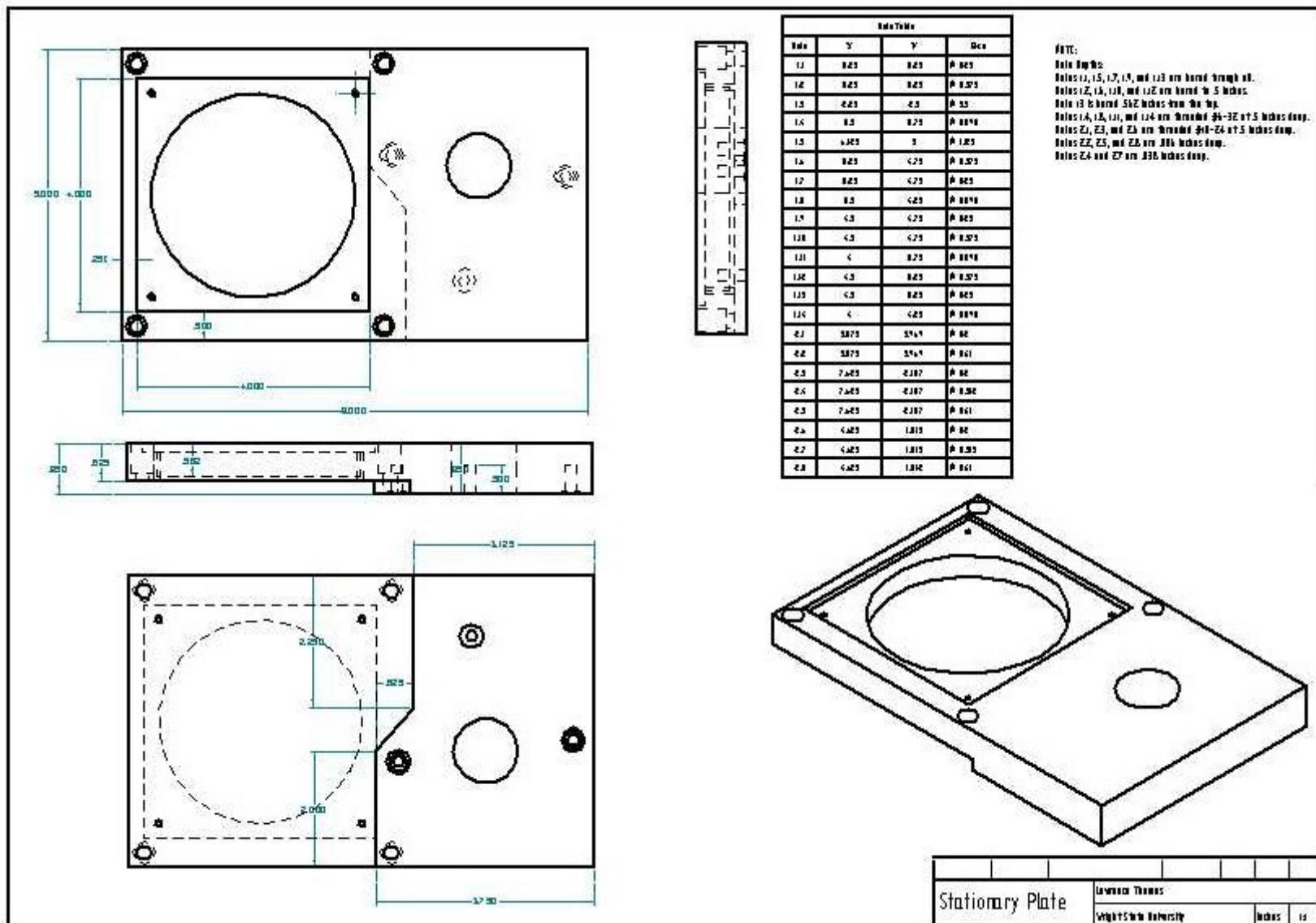
Shoulder Mount	Drawn By	Weight Shtk University	Revised	Date	10	10	10	10

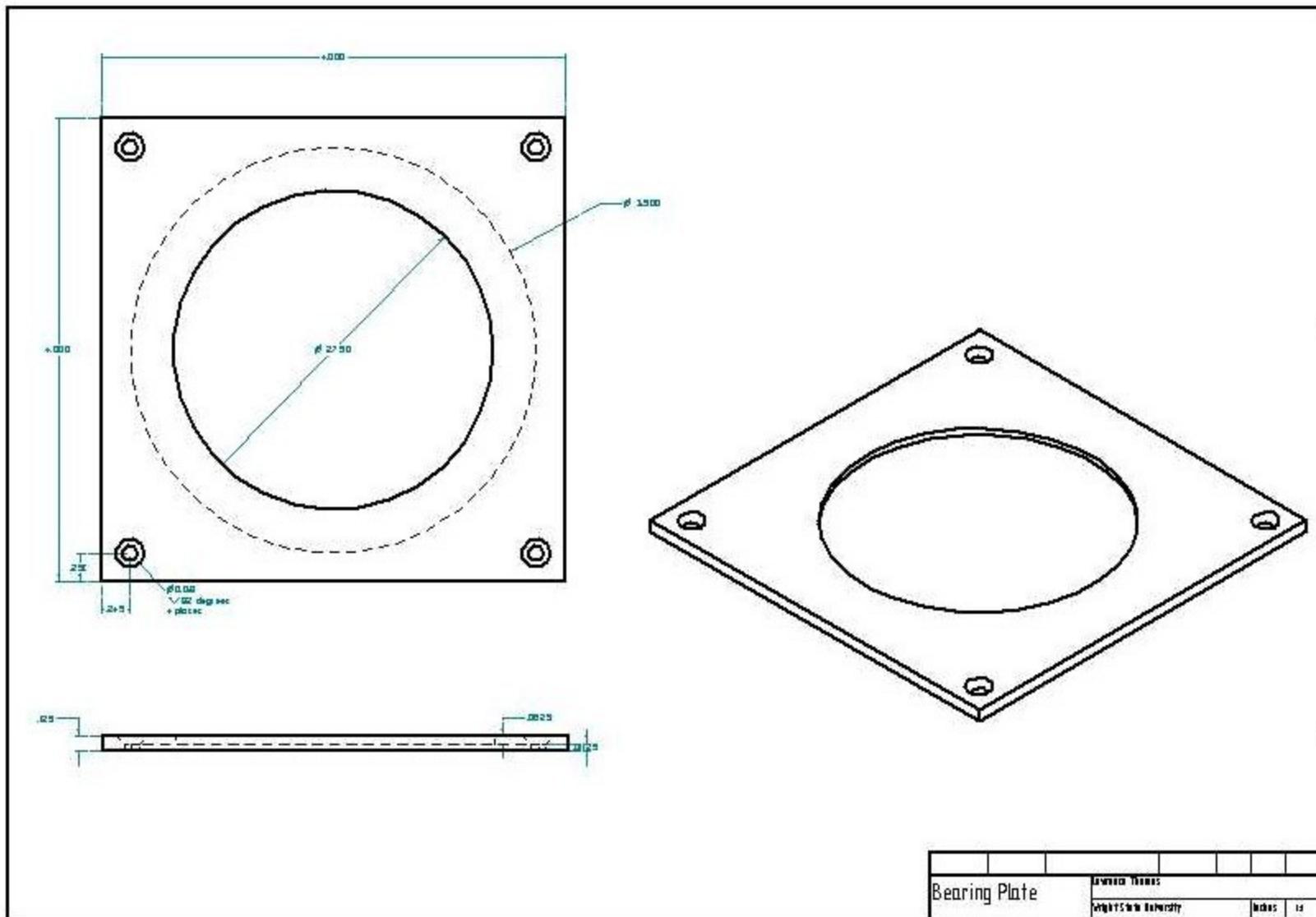


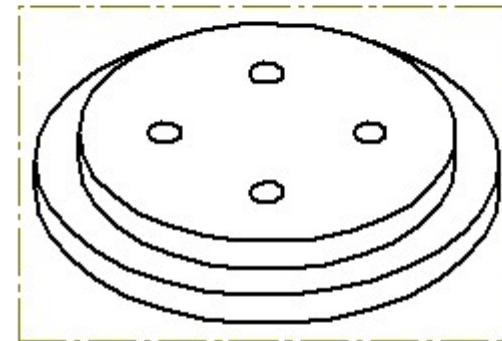
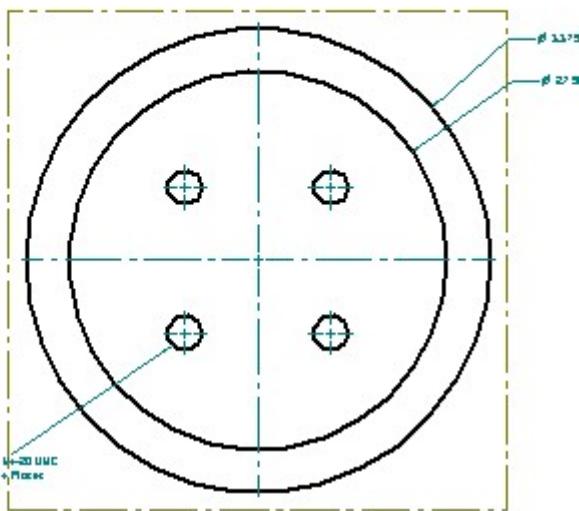


Shoulder Shaft	Weight & Unit Density
.000 lbs	15.000 kg

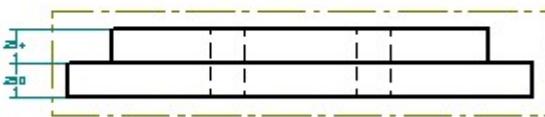




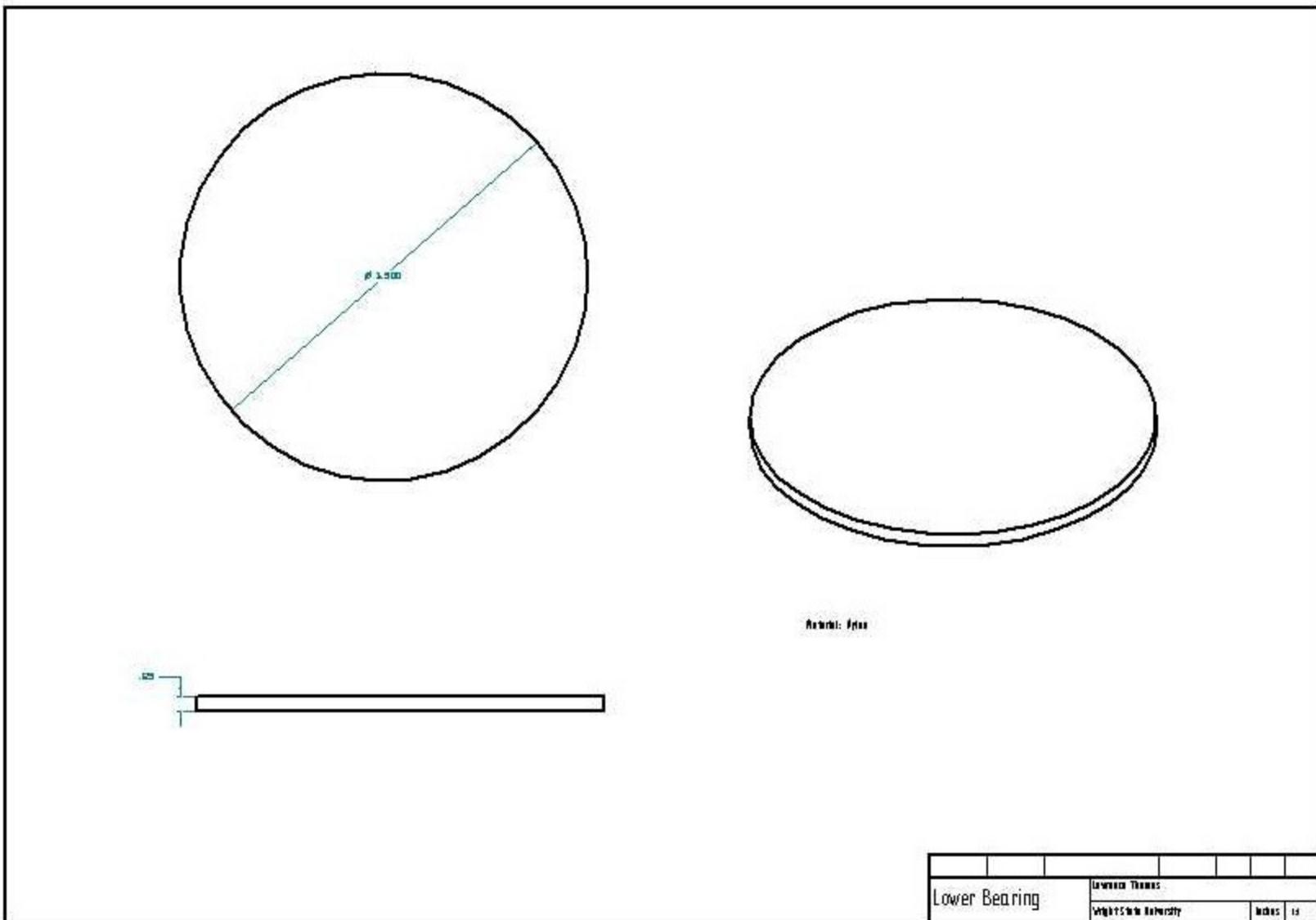


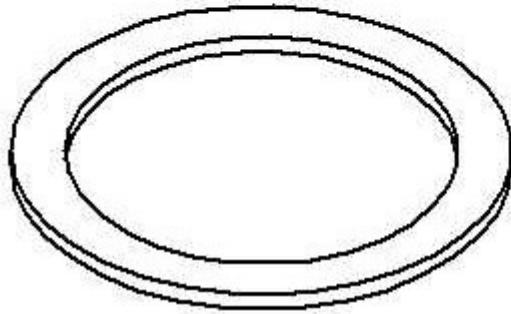
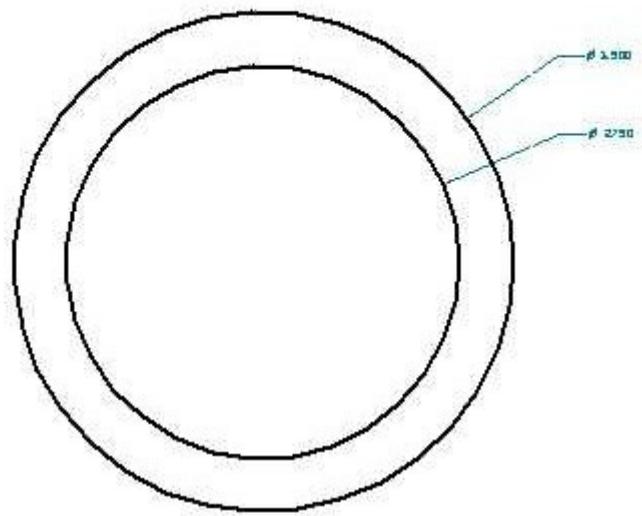


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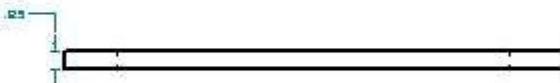


Center Bearing	Front Face	Front Taper	Front Width	Front Height	Front Depth	Front Material	Front Notes
Wright State University	Front Face	Front Taper	Front Width	Front Height	Front Depth	Front Material	Front Notes

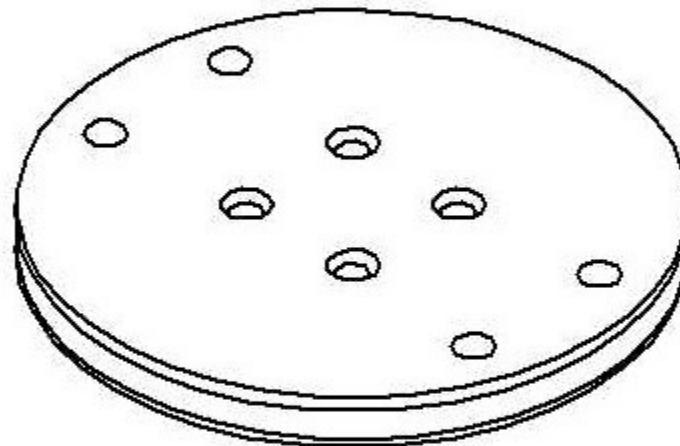
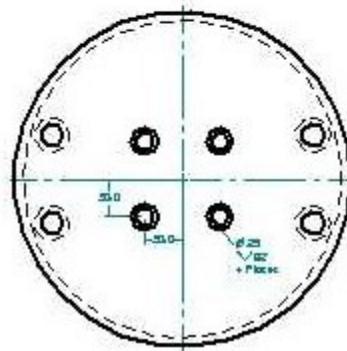
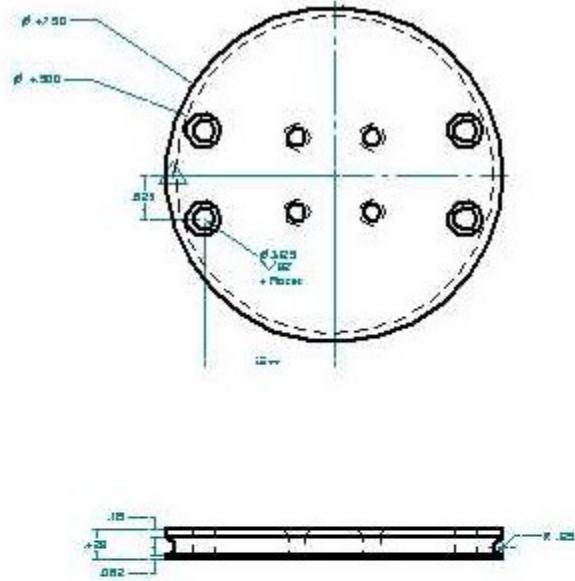




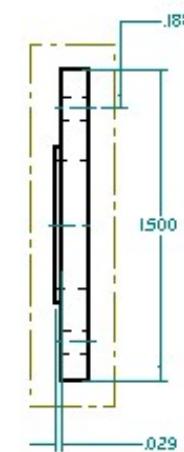
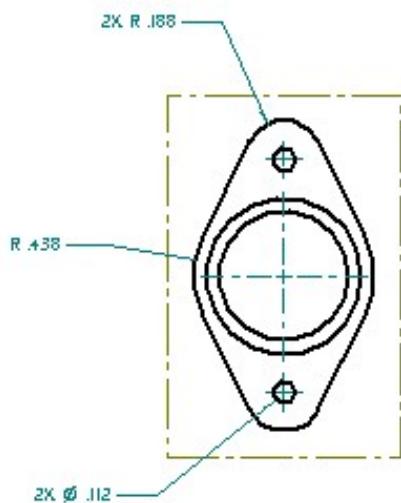
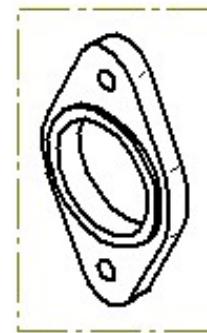
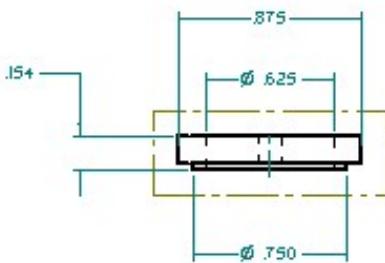
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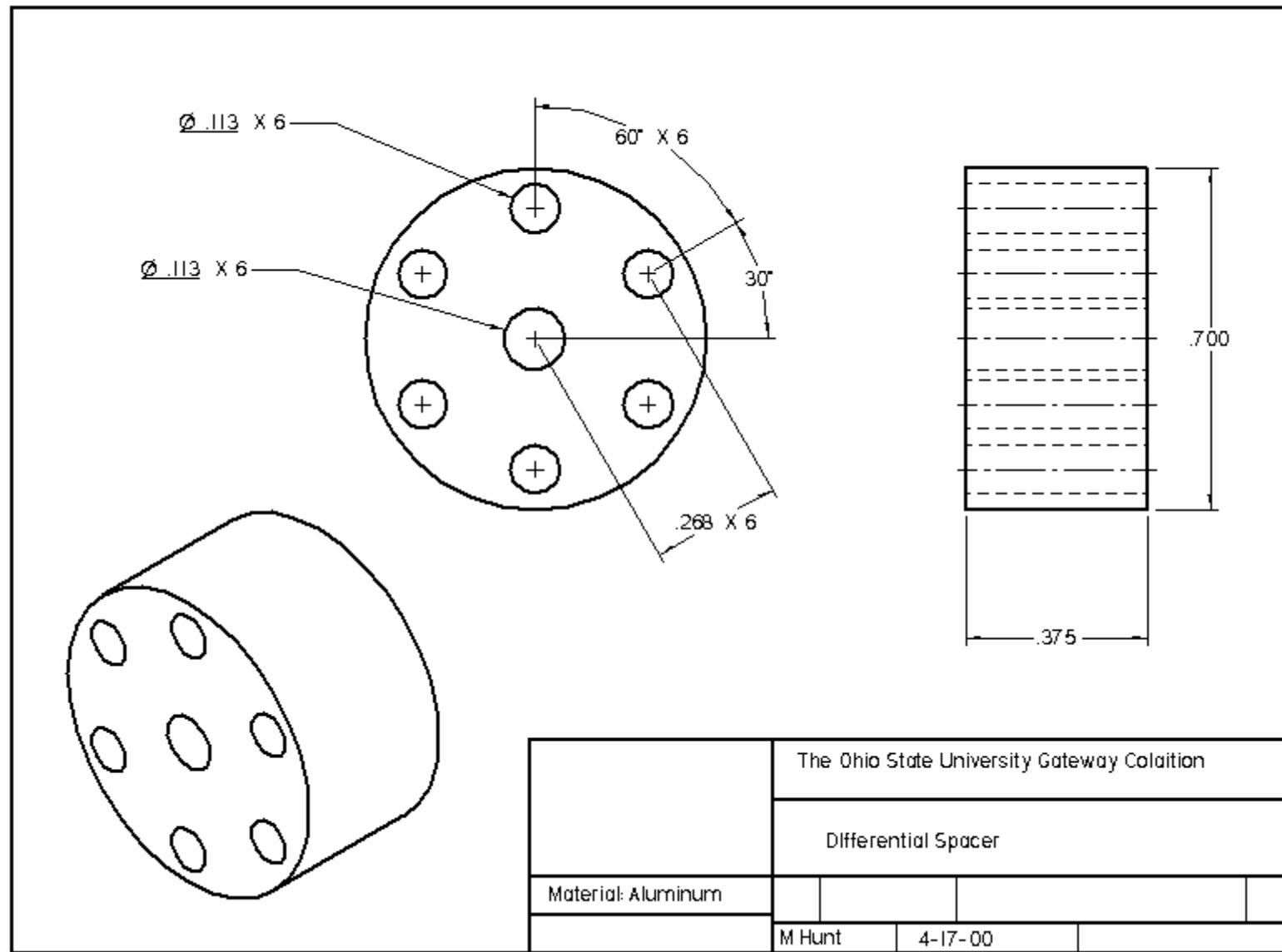
Upper Bearing	Author: Thomas	Wright State University	Index	13				



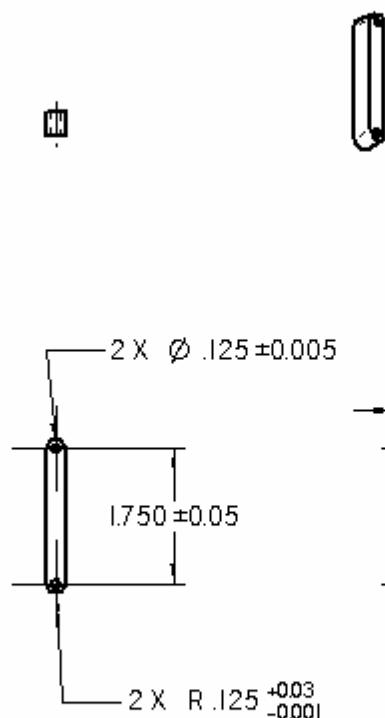
Twist Pulley	Process: Threaded	Wright State University	Index: 12
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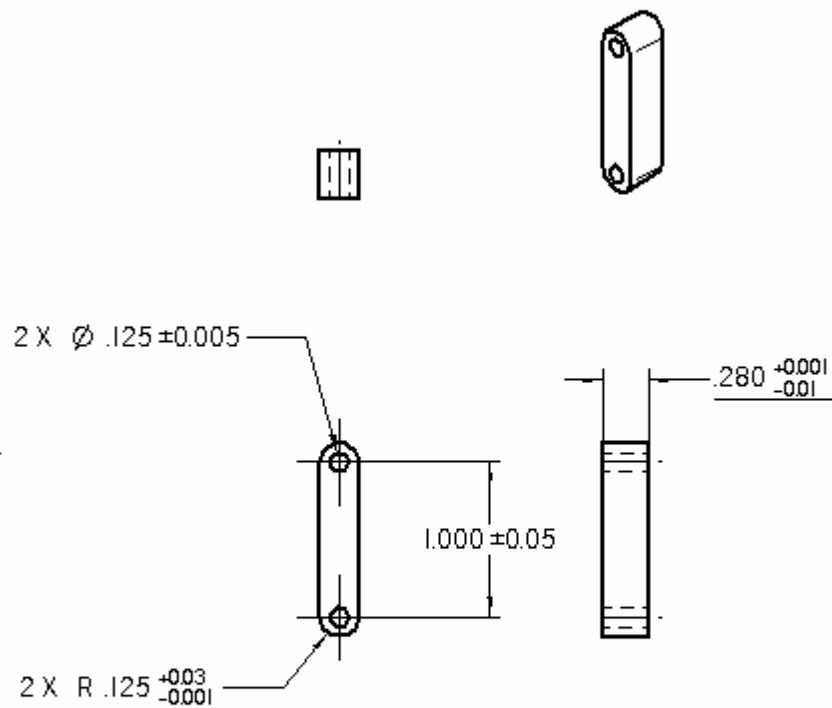
	QTY. - 2						
WRIST MOTOR PILLOW BLOCK REVISED 3/9/2001			WRIGHT STATE UNIVERSITY				
ERIC YU			NCHE S	I:I			



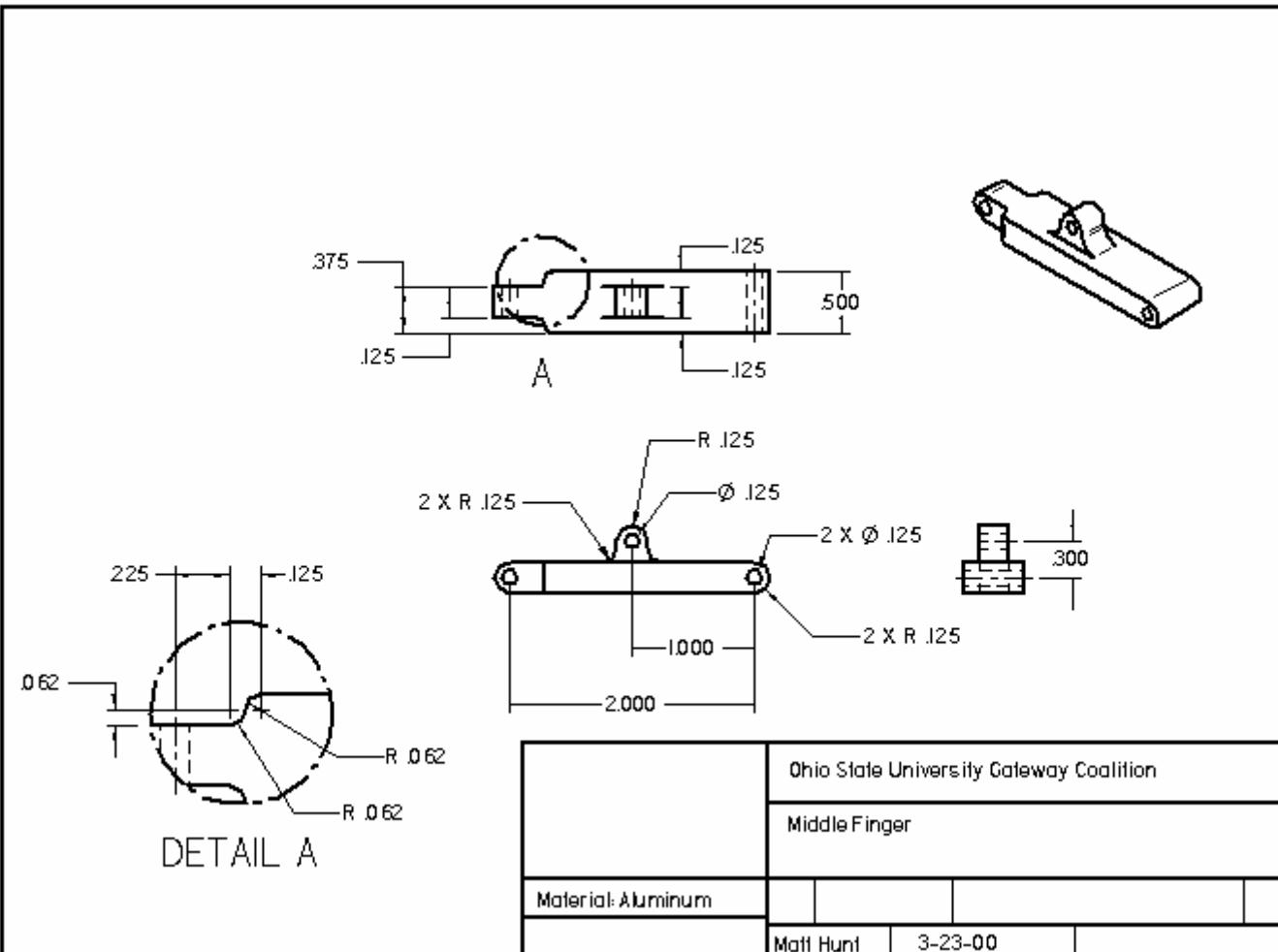
1.75" Link

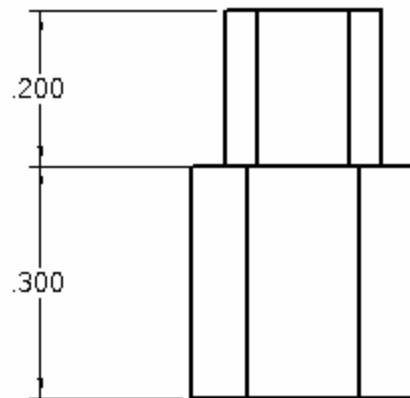
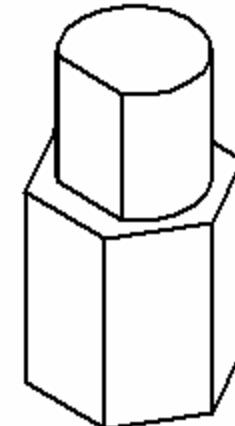
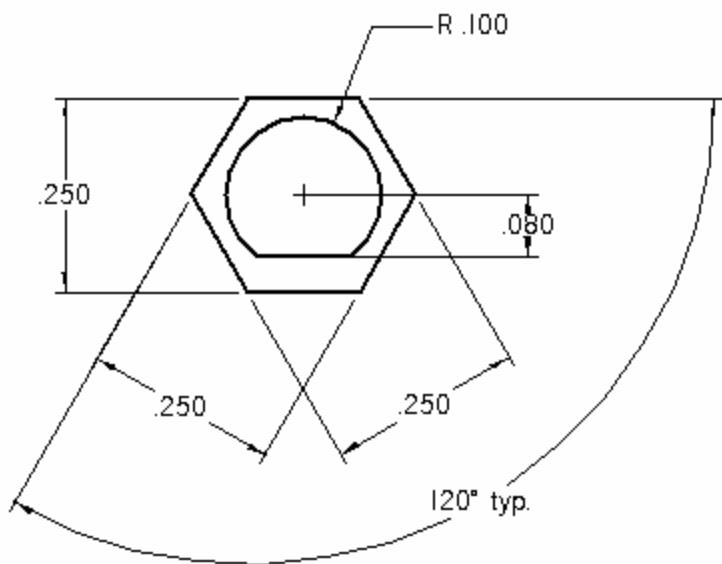


1.00" Link



	Ohio State University Gateway Coalition		
	1.75" Link & 1.00" Link		
		All Dimensions Inches	
Material: Aluminum	M Hunt	2-24-00	





All Tolerances ± 0.005
Unless Otherwise
Stated

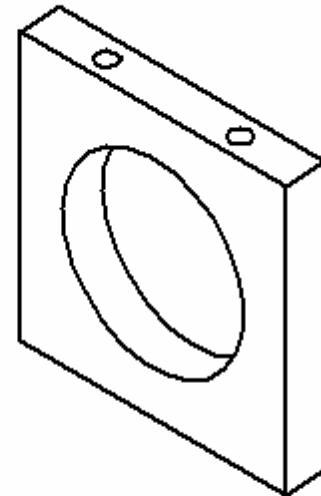
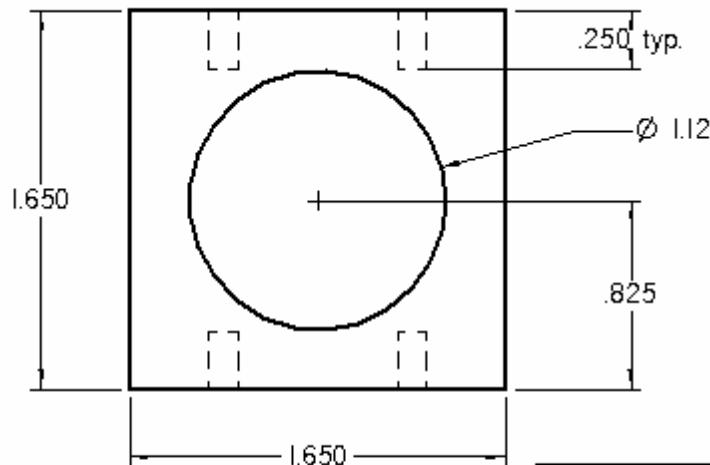
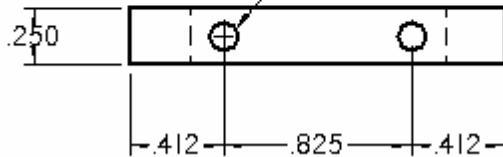
The Ohio State University Gateway Coalition

Motor Bit

Material: Aluminum

C. Johnson 02-06-01

#4 UNC Hex-head
Tap Size: #43
All 4 holes



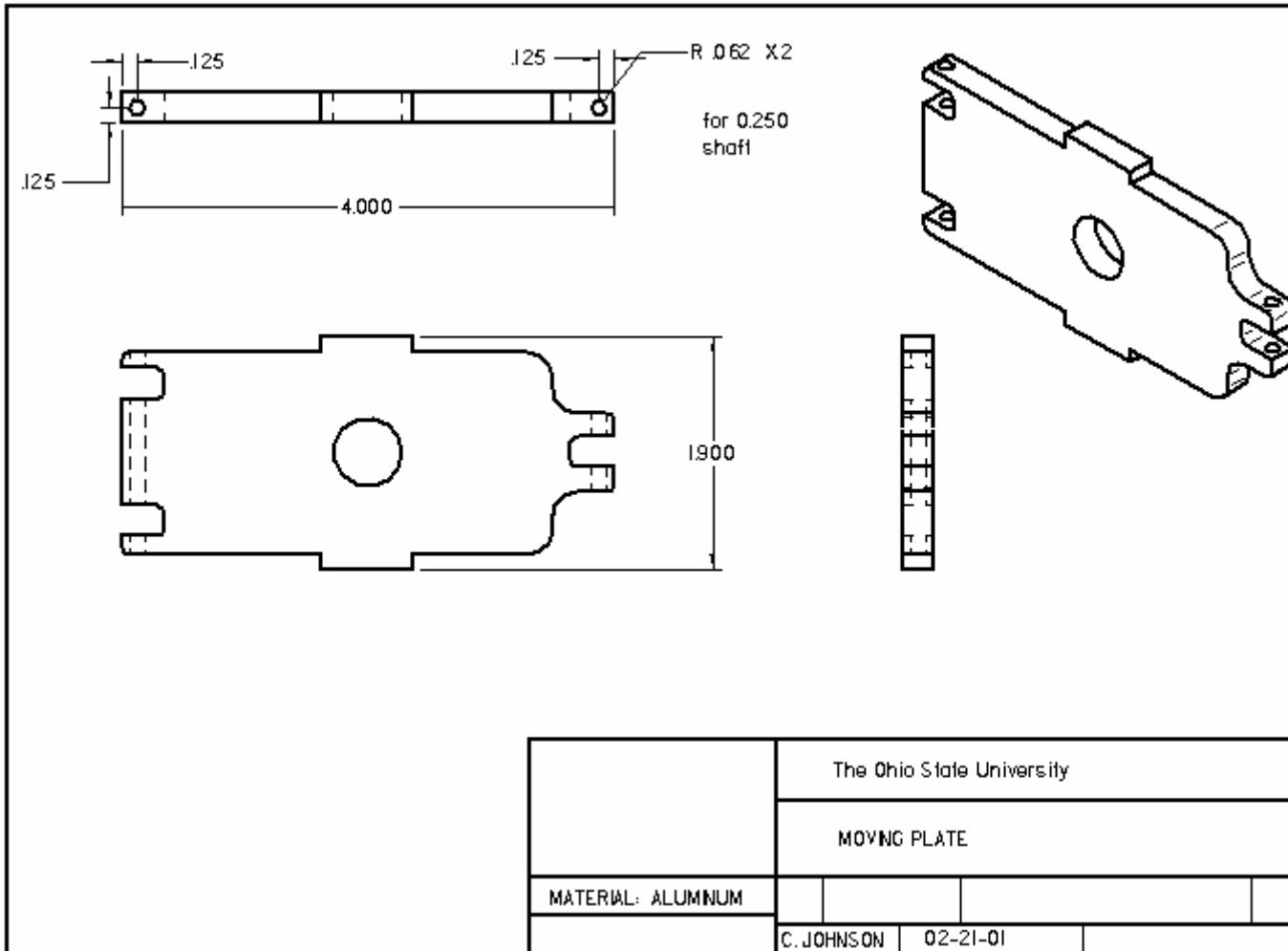
All Tolerances +/- 0.005
Unless Otherwise
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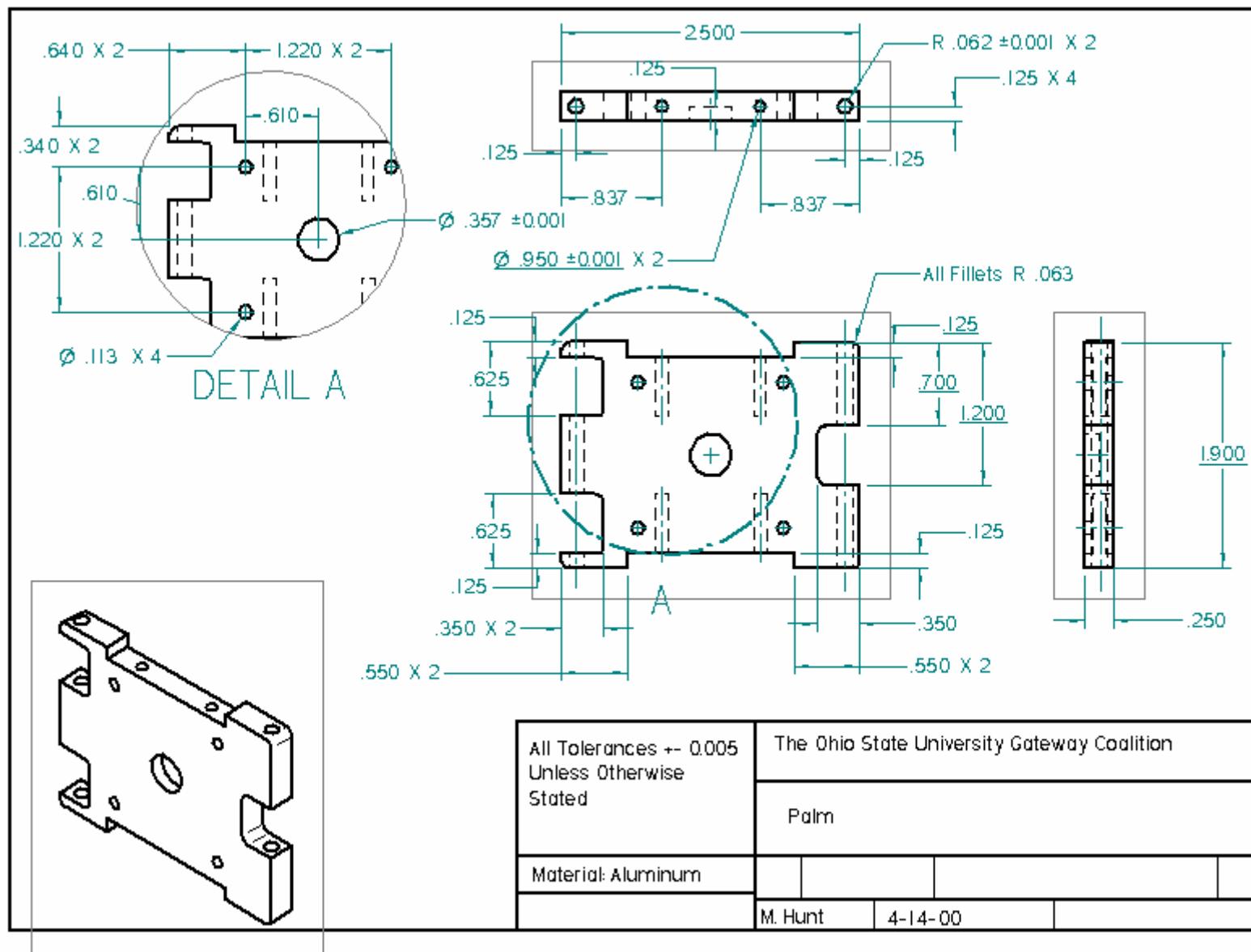
The Ohio State University Gateway Coalition

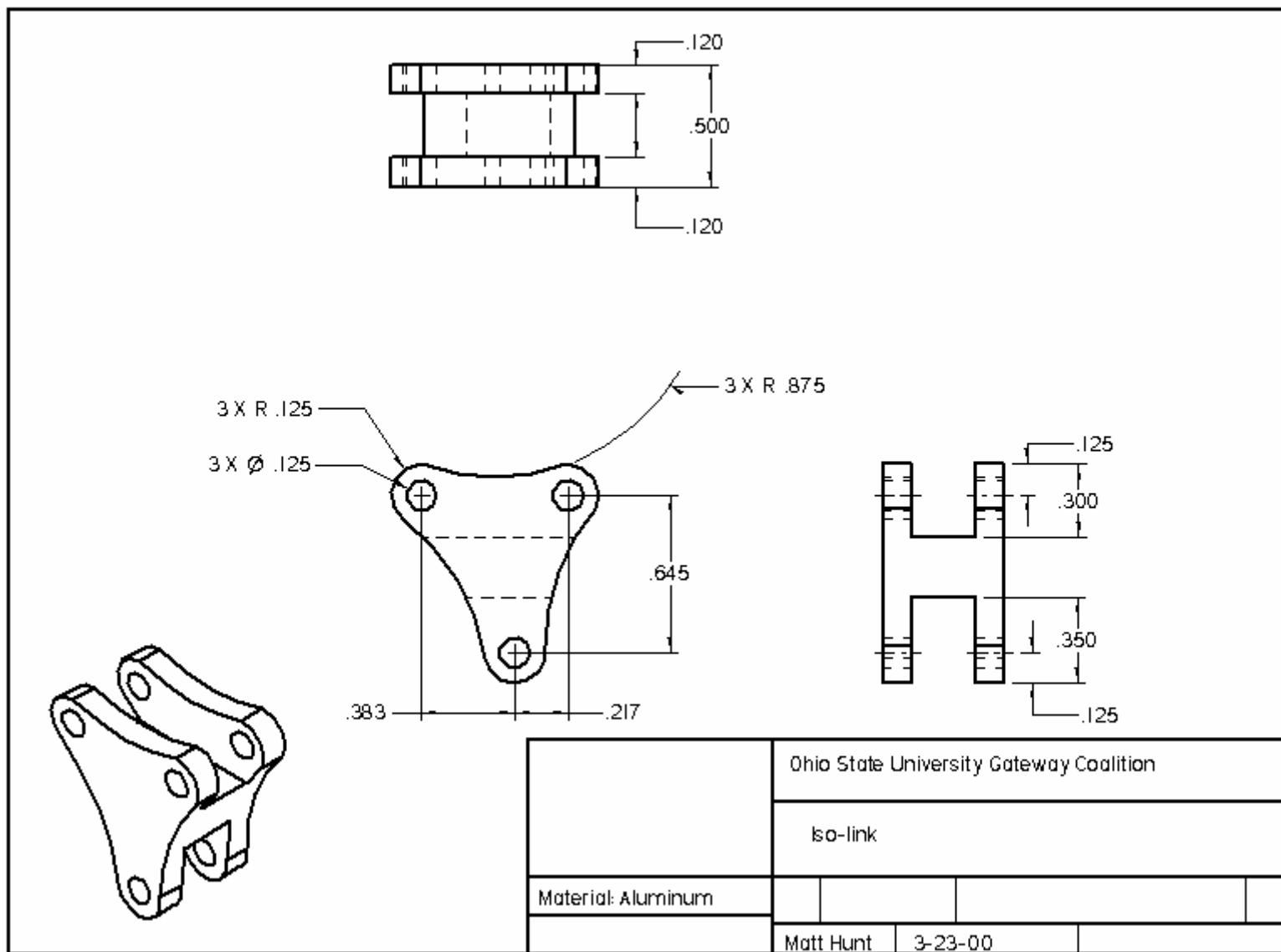
Motor Plate

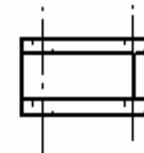
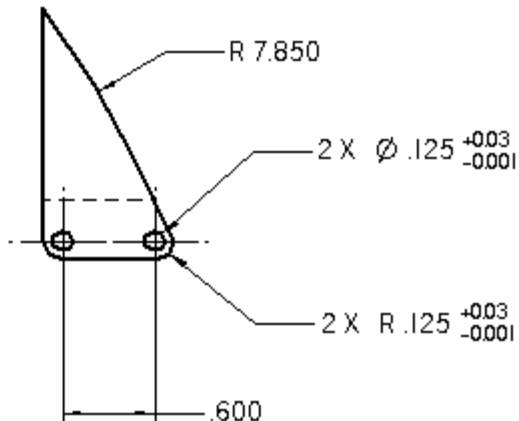
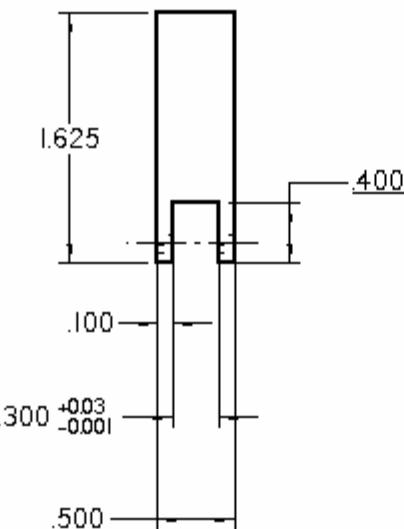
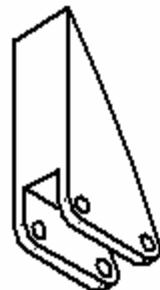
Material: Aluminum

C. Johnson 02-06-01









All Tolerances:
+ - 0.05 in
unless stated

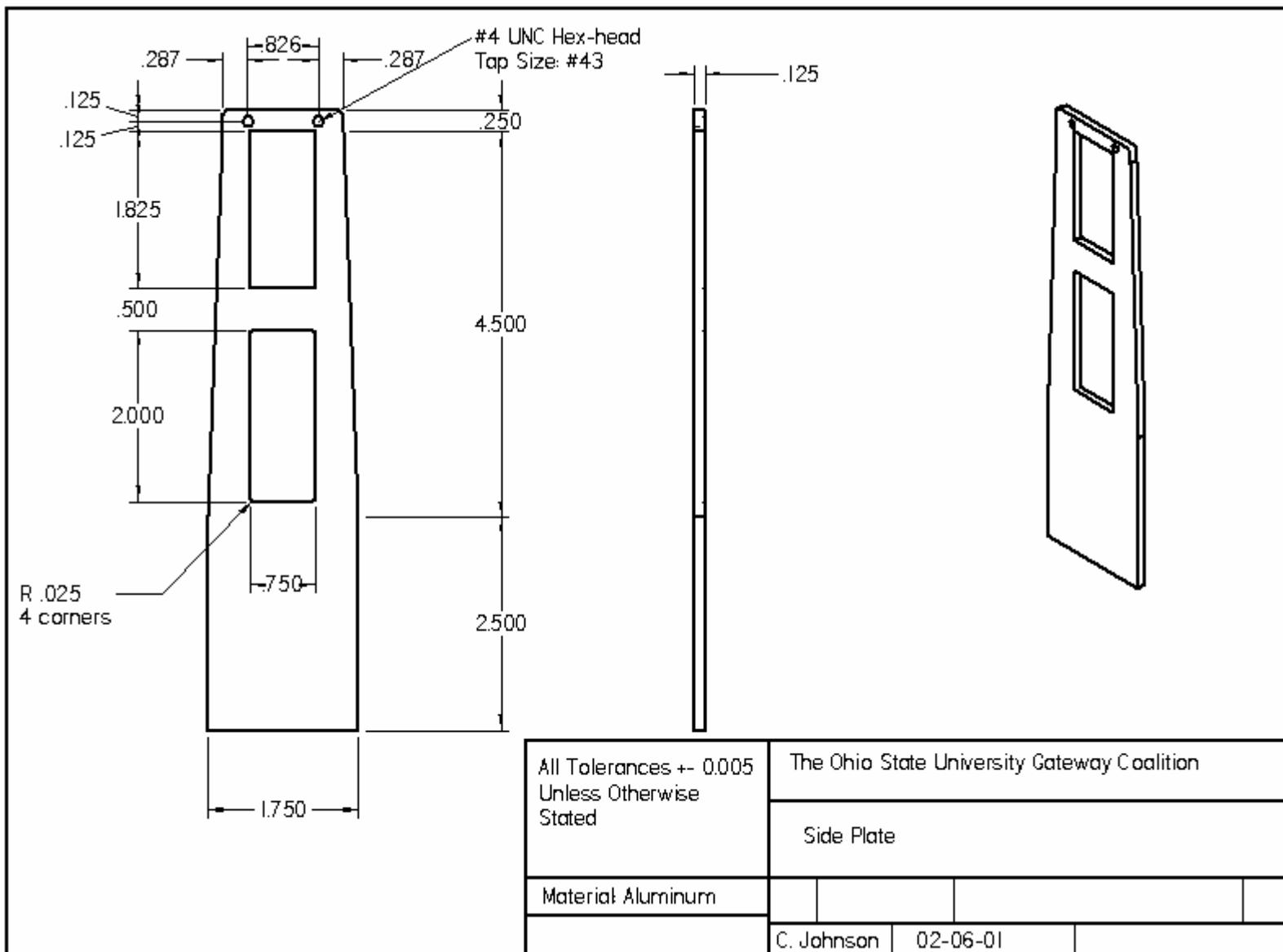
Ohio State University Gateway Coalition

Round Top Finger

Material: Aluminum

M Hunt 2-24-00

All Dimensions are Inches



REFERENCES

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ADDENDUM

DESIGN MODIFICATIONS

Following completion of the 2000-2001 design, two flaws were discovered but could not be addressed before the completion of the academic year. First, the belt driving the shoulder twist pulley was found to slip. It appeared that the Neoprene belt stretched under the stress of the pulley system. Second, binding occurred between the elbow gearing due to a lack of thrust support for both sides of the worm. Additionally, the two-part aluminum elbow shaft was too weak to support the forearm. The aluminum yielded from the stress of the steel pin securing the elbow worm gear to the shaft.

To eliminate slipping at the shoulder twist pulley, a stranded or V-shaped belt should replace the Neoprene belt. Because a stranded or V-shaped belt is less likely to stretch under tension, the belt will maintain high pressure around the pulley, eliminating slip.

To eliminate binding, components for the elbow were redesigned. The steel drive shaft for the screwdriver motor is elongated to enable placing a 0.434-inch stainless steel thrust bearing at the free end. A small aluminum block houses the thrust bearing and mounts within the lower arm tubing. The elbow motor is repositioned to accommodate the additional thrust bearing. See Figure AD.1 for the cutaway view of the elbow joint incorporating the thrust bearing.

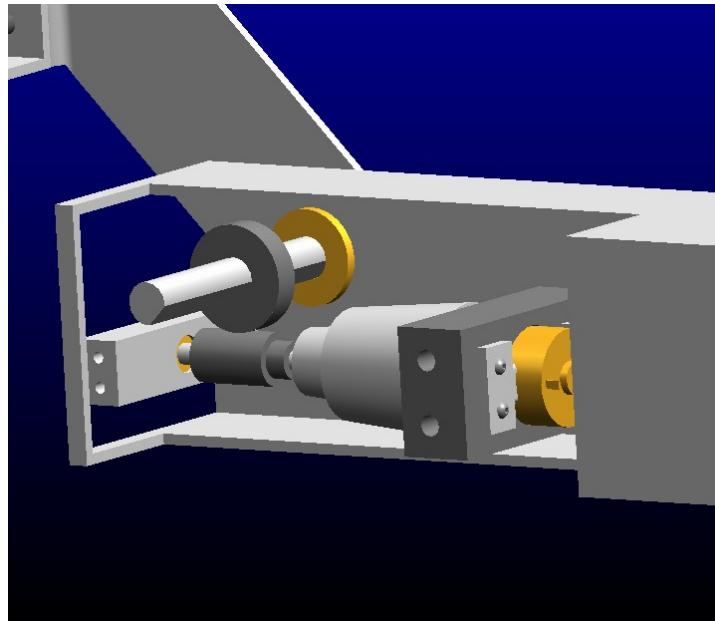


Figure AD.1 - Cutaway View of Redesigned Elbow Joint

Manufacturing the two-part elbow shaft design with steel is not possible because steel cannot be machined to the tolerances required for the design. Therefore, the two-part elbow shaft is replaced with a solid 0.25-inch diameter shaft. The repositioned motor requires the elbow shaft and worm gear to be offset within the lower arm tube. Finally, the elbow brackets were revised to still permit the forearm tubing to rest upon the lower arm tubing in the home position. Please see Figure AD.2 for the final elbow redesign.

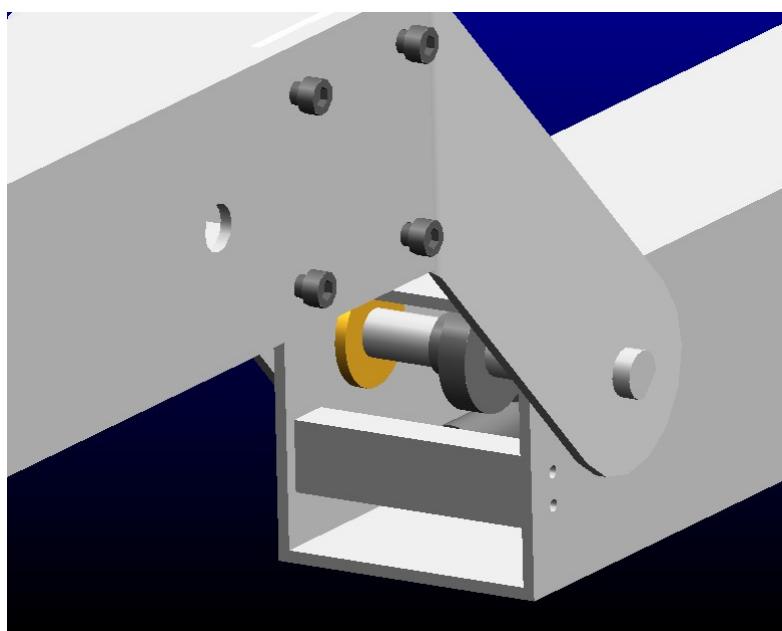


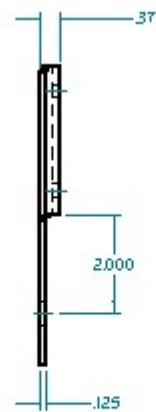
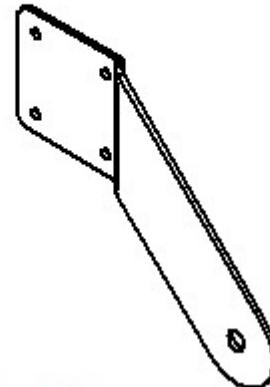
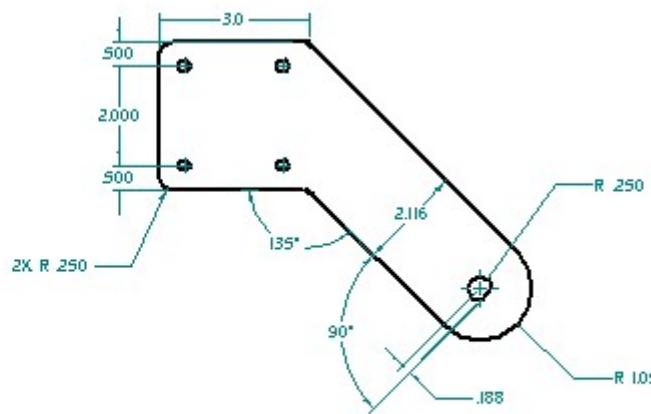
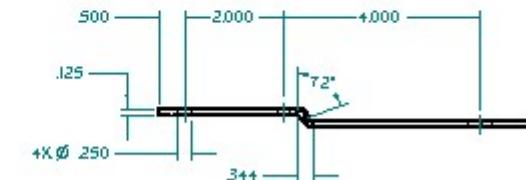
Figure AD.2 - Final Redesigned Elbow

While the design changes have not been evaluated for their feasibility, experimental performance during the final presentation for the 2000-2001 arm indicates that the modifications will adequately support the forearm. Since bearing support and the resizing of the elbow brackets were the only major modifications, the modifications will eliminate the flaws and produce a successful design.

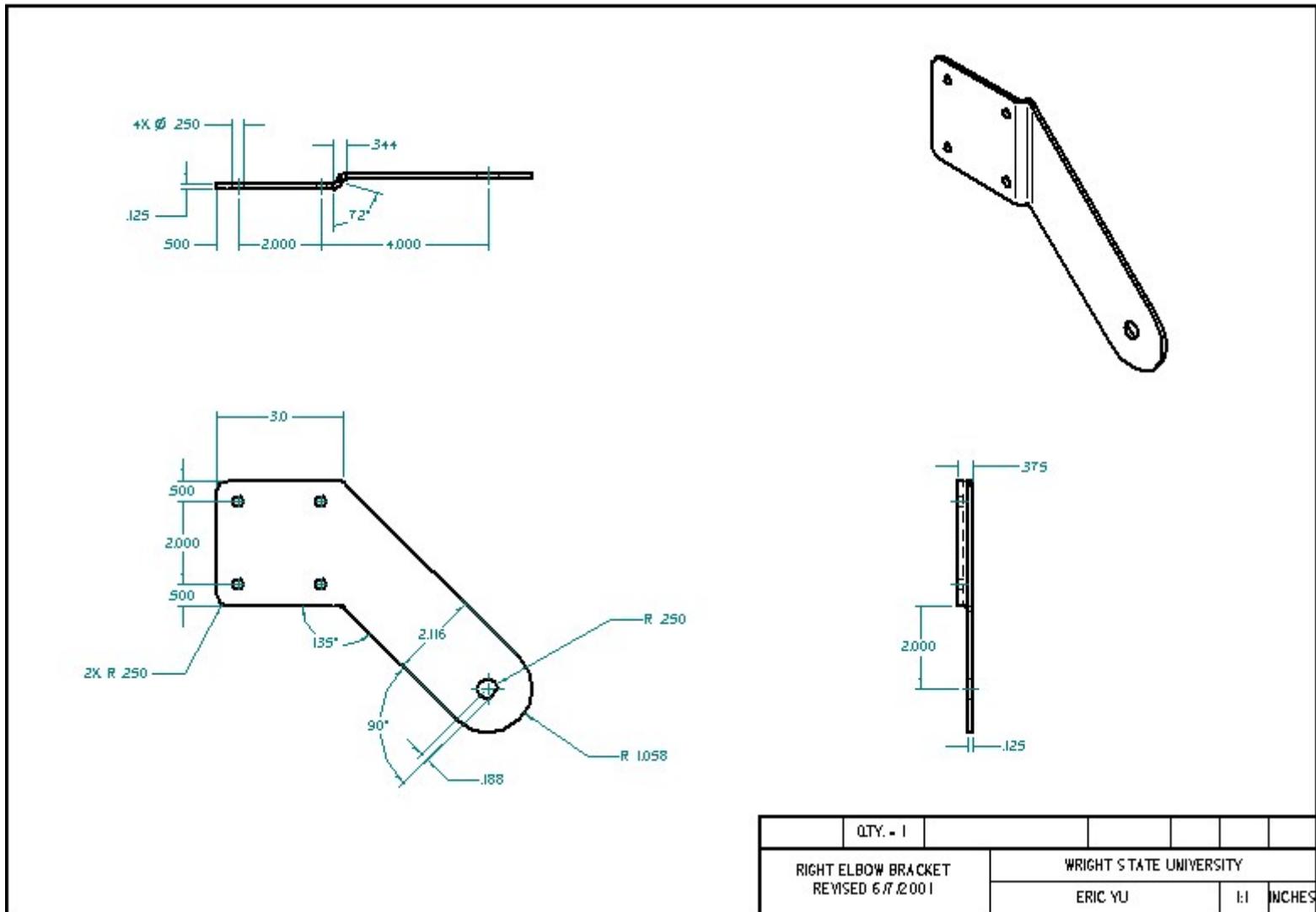
ELBOW REVISION BILL OF MATERIALS

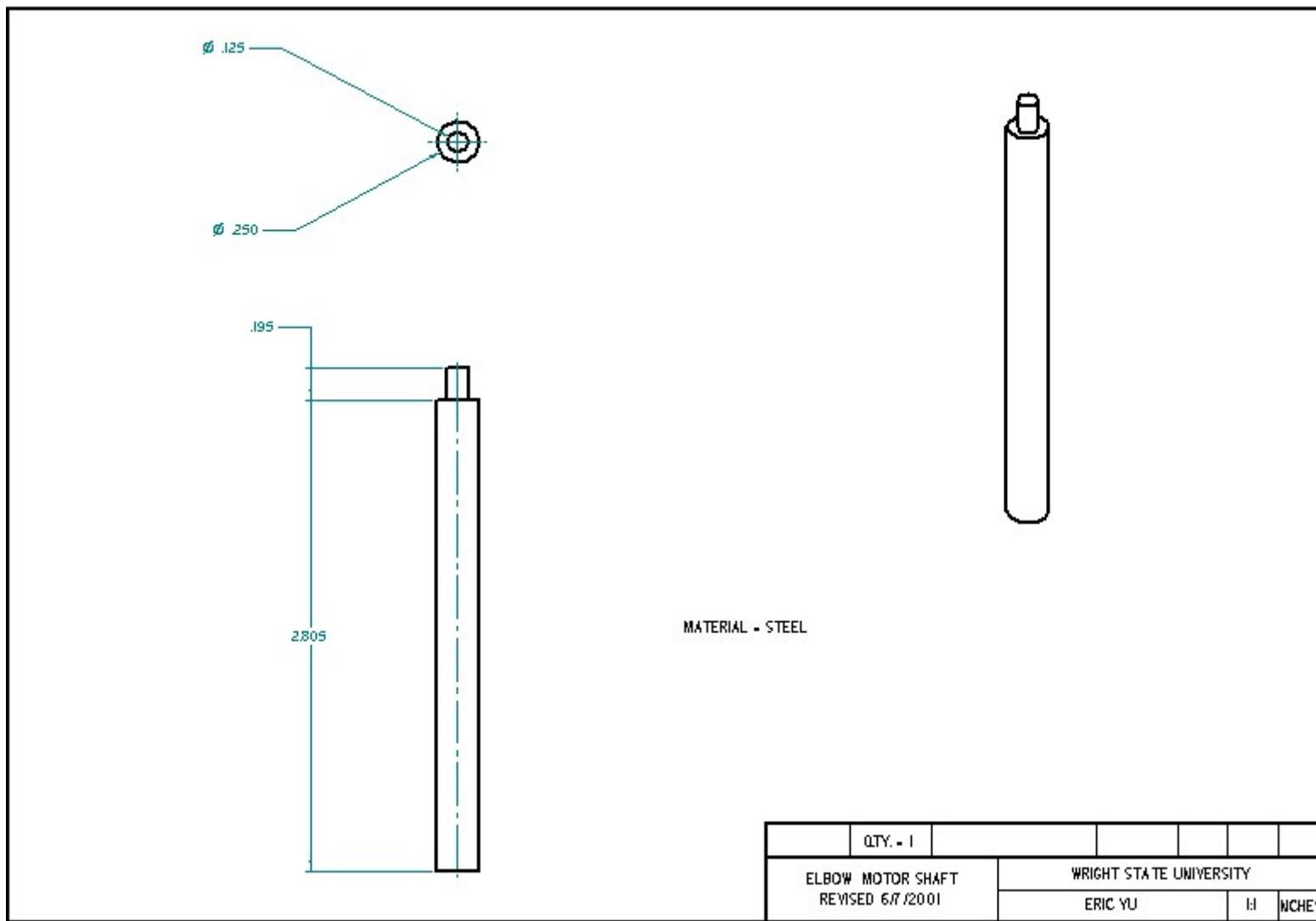
Table AD.1 – Elbow Revision Bill of Materials

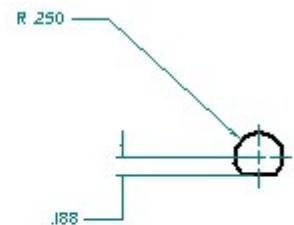
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	ET-02-5	PIC Design	1



Q.TY. - 1					
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ERIC YU		I.I	NCSES		

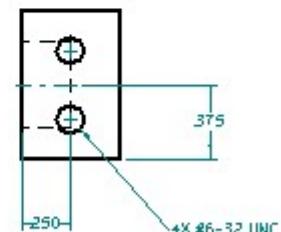
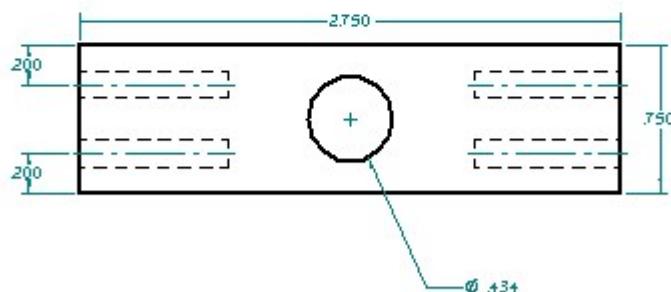
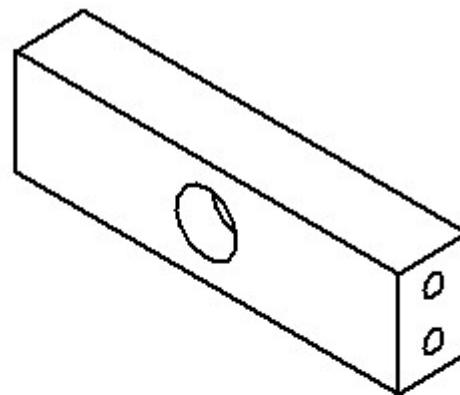
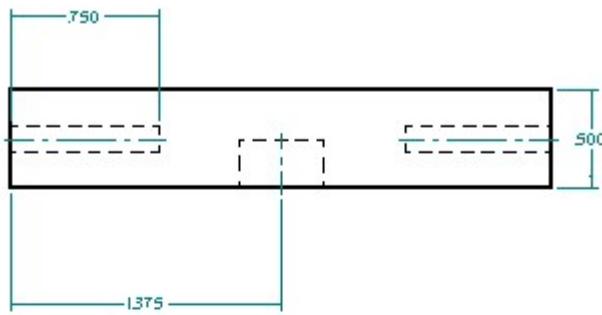






MATERIAL = STEEL

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ERIC YU			EI	INCHES			



	QTY. - 1					
ELBOW THRUST BEARING BLOCK REVISED 6/7/2001		WRIGHT STATE UNIVERSITY				
ERIC YU			1:1	INCHES		

